# Current Status and Challenges of Li-Fi: IEEE 802.11bb

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## Abstract

Existing and emerging applications of wireless networks require high data rates for multiple users, transmission security, uninterrupted connection, and no performance degradation in dense deployments. Light communications (LC) is a method that can potentially satisfy these challenging requirements. Exploiting the visible and infrared light spectrum opens the door for novel applications in the industrial and medical areas, and in enterprise and residential scenarios where traditional radio frequencies are restricted, prohibited, or inefficient. To enable LC in Wi-Fi networks, the IEEE 802.11 Working Group has launched a new 802.11bb standard. Although the work is currently ongoing, it is already possible to sketch a general view of the key innovations of 802.11bb based on the ongoing discussions in the group. This article reveals the principles of 802.11bb operation, highlights the key novelties, and points out actual problems that can be solved by researchers wishing to contribute to the development of LC in 802.11.


## Introduction

The continuous growth of user demands for fast, reliable, and secure communications combined with the spectrum crunch (i.e., the lack of wireless frequency spectrum needed to satisfy the growing demands) are causing developers of wireless communication technologies turn to light communications (LC). Wi-Fi is not an exception. Being the most popular last-mile technology, Wi-Fi suffers from severe interference in dense deployments [1]. That is why the Wi-Fi community is attempting to exploit the globally unlicensed visible and infrared spectrum. Having obtained much more spectrum than in the radio bands, the LC version of Wi-Fi, Li-Fi, has huge potential to provide much higher data rates than traditional Wi-Fi.

LC was justified within various technologies for personal area networks (e.g., IEEE 802.15.7, released in December 2011 and revised in December 2018). Its notable features include three physical layer protocols (PHYs) with data rates up to 96 Mb/s.

Unfortunately, such low data rates limit the applicability of the technology. In 2017, the 802.15 Working Group launched Task Group 13 (TG13) to increase the nominal throughput up to 10 Gb/s over line-of-sight (LoS) distances up to 200 m. Also, it extends the range of wavelengths to 190...10,000 nm. As of March 2022, the standard has undergone the third recirculation ballot and was planned to be submitted to the Standards Review Committee by May 2022. A downside of 802.15.13 is that it is designed for industrial applications. It does not target mass market consumers and will not be integrated into the ecosystem of existing widespread wireless networks. Also, 802.15.13 is designed for LoS scenarios, whereas many practical use cases are non-LoS. Moreover, the joint operation of the LC and radio frequency (RF) technologies is out of the scope of 802.15.13.

In contrast, Wi-Fi technology, based on the 802.11 standards, has a wide range of use cases, a well-established ecosystem of consumer electronics, and a huge market that allows reducing the per-device cost. Li-Fi plans to inherit these properties. Additionally, Wi-Fi supports multi-band operation, potentially allowing LC to work together with 2.4/5/6 GHz bands using existing medium access control (MAC) sublayer functionality and native LC-RF interface switching.

Alongside TG13, the 802.11 Working Group launched Task Group bb (TGbb) with some of the same leaders and main contributors of TG13 to create an LC standard compatible with Wi-Fi. Using the 802.11 MAC and reusing the existing 802.11 services, 802.11bb addresses a broader range of use cases than just low data rate photodiode communications (802.15.7m) and industrial applications (802.15.13). Moreover, TGbb intends to allow universal 802.11 components for both RF and LC, which is especially valuable for operators and manufacturers. The benefit of joint RF and LC operation is also fruitful for the following reason. Although 802.11bb will provide high data rates with LC in LoS cases, opaque obstacles easily drop the connection. To overcome this issue, 802.11bb can switch between the new LC PHY and the existing 802.11 RF PHYs. For that, 802.11bb inherits Fast Session Transfer, introduced in 802.11ad defining millimeter-wave (mmWave) communications.

Notably, 802.11 already had an Infrared physical layer for the light spectrum in 1999, but it had no actual implementations and was eventually deprecated. As the current Wi-Fi technology supports 1000 times higher data rates and extensively more features, it is much easier to design a new PHY instead of reviving the legacy infrared protocol to achieve performance of LC comparable to that of RF. For that, TGbb has much discussion on whether to adapt existing RF PHY to LC spectrum

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LC has significant market potential. Its use cases cover all traditional scenarios of Wi-Fi with the restriction that radio frequencies are not desired or are inefficient. They include industrial wireless, wireless access in healthcare facilities, corporate and home networks, backhaul networks, underwater communications, and more.

or to introduce a completely new 802.11 PHY. Although TGbb has chosen the first option to speed up the development process, we believe that the discussed and postponed ideas indicate directions for next-generation Li-Fi.

These observations motivate us to comprehensively investigate the main features of 802.11bb, raise open issues, and explain the promising research directions that may boost the performance of future Li-Fi, which is the main contribution of the article. The rest of the article is organized as follows. We review the 802.11bb timeline. We dive into the use cases for Li-Fi and corresponding channel models. We describe new features related to waveform generation, PHY, and MAC protocols. We discuss open issues and possible directions for Li-Fi beyond 802.11bb. Finally, we summarize the future research directions of Li-Fi.

## 802.11bb Timeline

The work on 802.11bb began within the LC Topic Interest Group in late 2016. Its goal was to study the applicability of LC and substantiate its technical and economic feasibility. They estimated the LC market size to grow over $10 billion in the next few years [2]. They also found that various LC vendors had non-standardized products for many use cases that could have significant market growth. Moreover, they predicted that a standardized technology would make LC devices cheap, small, and energy-efficient. and facilitate bringing LC to the mass market.

In May 2017, the group was reorganized into a Study Group. During this phase, the group explored the technology use cases, identified the key performance indicators, and proposed an initial view on usage models.

Next, in July 2018, the group acquired the status of the 802.11bb Task Group, TGbb. The group approved the scenarios, functional requirements, channel models that will be used further for evaluation. An initial Draft 0.1 was completed in January 2020. The current version is Draft 1.0, published in December 2021. According to the latest timeline revised in July 2021, the group expects to finalize the standard by the end of 2022.

## 802.11bb Usage Models

LC has significant market potential. Its use cases cover all traditional scenarios of Wi-Fi with the restriction that radio frequencies are not desired or are inefficient. They include industrial wireless, wireless access in healthcare facilities, corporate and home networks, backhaul networks, underwater communications, and more. Based on these cases, TGbb has proposed several usage models.

For example, in the *industrial wireless* usage model, a radio network suffers from strong electromagnetic interference. In a large metal-walled factory housing automated robots and other manufacturing equipment, LC can be deployed to provide reliable wireless connectivity.

The applications include ultra-high definition video streaming for surveillance, industrial monitoring, and video communications. LC can serve for real-time ultra-reliable command and feedback transmission. Multiple LC modules are deployed on the equipment and on the ceiling/walls to provide multiple light links for robust connectivity even when a single LoS link is blocked. Interference may occur due to close placement between signal sources and other light sources. Notably, LoS blockage and the presence of interference are two common challenges in all the TGbb usage models.

Another usage model is *wireless access in the medical environment*, where RF is prohibited. LC can control medical equipment, deliver remote medical services, and enable communication between medical staff.

The *enterprise network* usage model assumes a large number of users, which limits the RF applicability. Moreover, security or privacy concerns are a limiting factor. 802.11bb will allow mounting a light source access point (AP) per user at a 1...3 m distance, avoiding interference. As light does not pass through walls, 802.11bb will improve privacy. LC can be used for fast file exchange, videoconferences, and intranet/Internet access.

The *secure home network* usage model addresses the security issue. Besides security, optical communication will provide high throughput for applications such as virtual reality, Internet access, and online video chat. LC APs can be densely deployed in every room where wireless connectivity is required, and only a few of them will be obscured by, for example, furniture.

In addition to the aforementioned primary usage models, TGbb considers such secondary usage models as wideband backhaul, vehicular communications, underwater communications, and communications in gas pipelines. TGbb has prepared a collection of reference channel models that describe the environment properties, channel characteristics, and simulation parameters for these usage models. They can be found in TGbb documents [3]. With these models, one can yield a channel impulse response (CIR) from each light source to each detector. Some models already have ready-to-use simulation scenarios with all objects in the scene, their location, and their reflective properties [4]. Additionally, TGbb has made several CIRs available that can be downloaded from [5].

## 802.11bb Waveform and LC Frontend

### Waveform

The core idea of 802.11bb is to optimally reuse the existing 802.11 functionality and introduce only the most necessary features that enable LC. 802.11bb reuses the existing waveform generation procedures. Since 802.11a, Wi-Fi has used orthogonal frequency-division multiplexing (OFDM). But OFDM cannot be used directly in LC systems, which utilize the intensity modulation and direct detection (IM/DD) method to transfer data. To allow an OFDM-based approach, TGbb uses DC-biased optical OFDM (DCO-OFDM). It is a carrier-based intensity modulation, where a transmitter induces a carrier by periodically varying light intensity and modulates this carrier with conventional OFDM. Compared to a simpler pulse-based intensity modulation used in 802.15.7 and 802.15.13, DCO-OFDM is less susceptible to inter-symbol interference, thus supporting higher data rates.

To transform a complex-valued and bipolar OFDM signal into a real and non-negative DCO-

OFDM signal, a device upconverts the original OFDM signal to a real signal and then biases it by a positive direct current (DC) component. As shown in Fig. 1, such transformation of an OFDM signal of bandwidth *BW* to a real waveform shifts its center frequency by $BW/2 + \Delta$. The additional margin $\Delta$ is crucial for preventing the signal from aliasing. As Fig. 2 shows, a larger $\Delta$ reduces the aliasing effect better. Using $\Delta$ = 1.5 MHz in a channel with bandwidth 20 MHz causes lower packet error rate (PER) than $\Delta$ = 0.5 MHz because of the aliasing effect. However, too high $\Delta$ deteriorates the signal significantly because of the channel's low-pass filter characteristics [6]. Using $\Delta$ = 30 MHz significantly increases PER, as the signal attenuates more at higher frequencies. The optimal $\Delta$ depends on the channel width [7] — the higher bandwidth requires a larger margin for low bit error rate (BER). However, for consistency, TGbb has chosen one value, $\Delta$ = 16 MHz, which diminishes the aliasing effect for all channel bandwidths from 20 MHz to 160 MHz, used in traditional Wi-Fi [1].

### LC Frontend

Since 802.11bb introduces a new light medium to 802.11, TGbb has designed an LC frontend model. This model includes a transmit and a receive frontend, and they are vital to evaluate the impact on the communication channel and the resulting imperfections in the signal.

The LC transmit frontend contains a digital signal processor, an LED, and an LED driver (Fig. 3a). The processor gets a frame and outputs an analog signal. Custom-designed for each LED, the driver amplifies the signal and performs impedance matching. From the mathematical point of view (Fig. 3b), the driver comprises the *N*th low-pass Butterworth filter and the first order high-pass one. The high-pass filter is implicitly included in the LED driver, as it is necessary for a fair comparison between the pulse modulation and OFDM. Next, the signal is biased so that the resulting voltage at the electro-optical converter's input is always non-negative.

Figure 3c shows an LC receive frontend consisting of a photodetector, a transimpedance amplifier, and a digital signal processor. The amplifier, similar to the LED driver in the transmitter, matches the impedance of the detector and the signal processor. In the mathematical model in Fig. 3d, the high-pass filter cancels the DC bias introduced by the transmitter. The low-pass filter after the amplifier cuts out the intended frequency band. Notably, [8] proposes parameters for the frontend models to match the measurements of real LC frontends.

### Channel Numbering

TGbb admits that an LC station may include an RF station as its architectural part. In such a case, an RF station generates an RF signal in the 2.4/5/6 GHz band. Then the signal is converted to an LC one. Hence, an LC station needs to map all the RF channels to LC channels. 802.11bb defines the channels of various bandwidths. The center frequency of channel $n_{LC}$ is $(21 + n_{LC}*5)$ MHz [9]. All 20 MHz channels from the 2.4 GHz band are mapped to the channel $n_{LC}$ = 1. The 5 GHz channels with indexes $n_{5GHz}$ = 36…64 are mapped to $n_{LC} = n_{5GHz} - 35$. The 6 GHz channels with indexes $n_{6GHz}$ = 1…29 are mapped to $n_{LC} = n_{6GHz} + 32$. The band of LC channels is the same as the corresponding channels in 5/6 GHz bands.

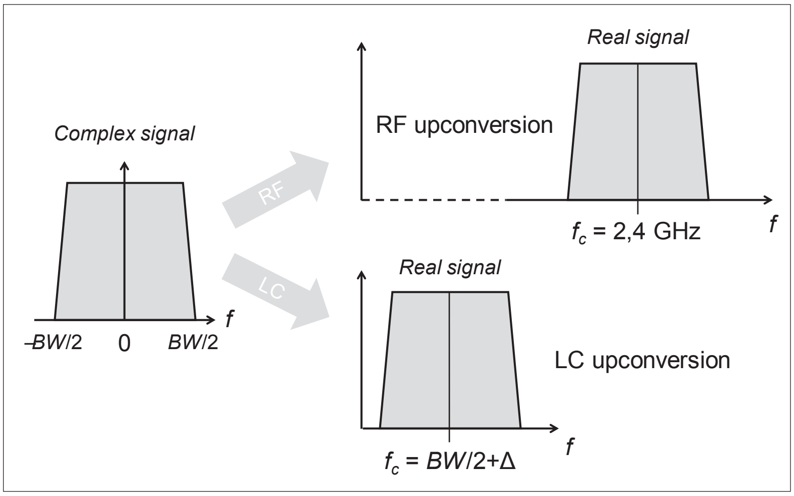


**Figure 1.** Upconversion of a complex baseband signal in RF and LC cases.

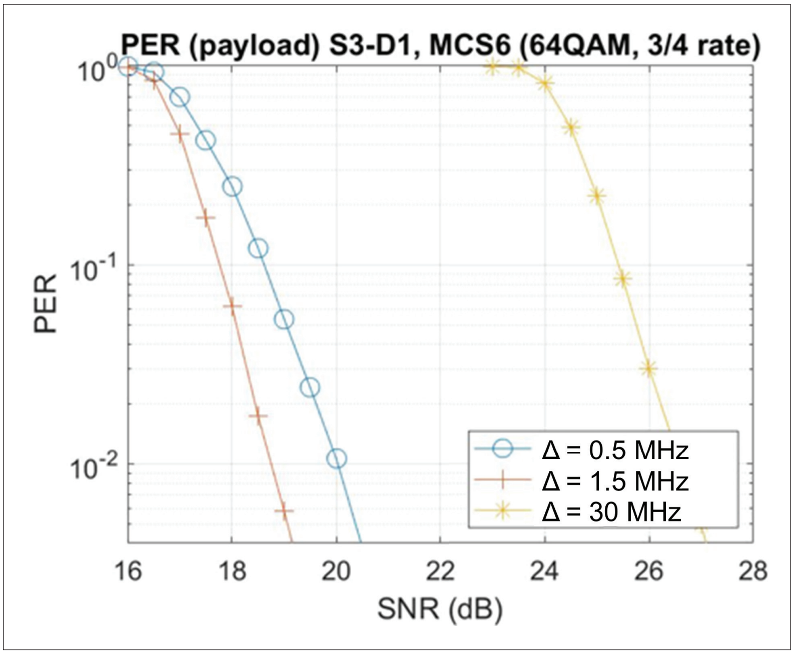


**Figure 2.** Packet error rate (PER) vs. SNR for various margins $\Delta$ and the 20 MHz bandwidth (adapted from [7]).

## Physical Layer

### Initial Discussion

TGbb has had intense debates on the basic PHY paradigm. The first option is the existing 802.11 PHYs shifted to LC frequencies; the second option is an adaptation of an LC-optimized (LCO) PHY [10] standardized in International Telecommunication Union Telecommunication Standards Sector (ITU-T) G.9991 (G.vlc). The first option minimizes efforts for a viable solution, while the second one increases throughput and robustness thanks to adaptive bit loading.

The adaptive bit loading technique allows varying modulation per subcarrier independently. It allocates more bits (i.e., uses higher-order modu-

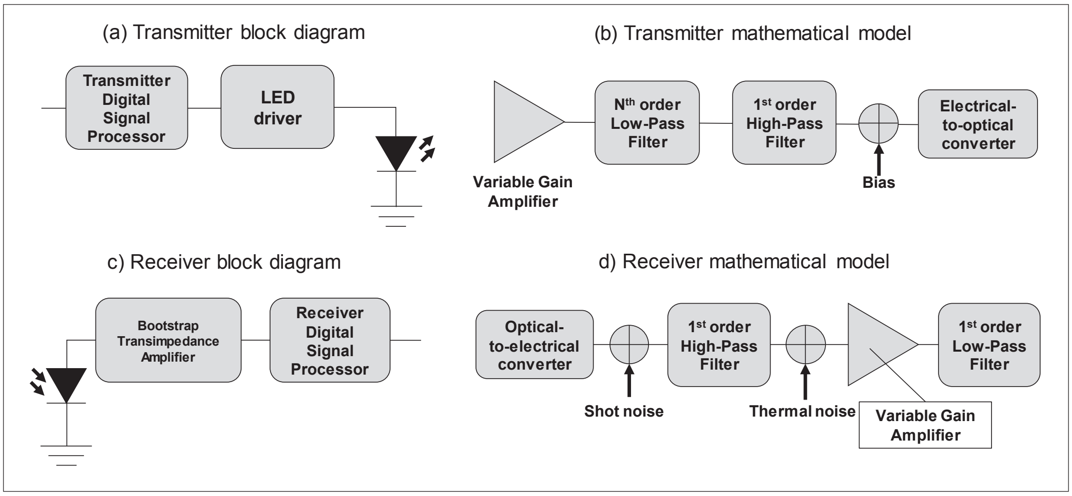


**FIGURE 3.** Block diagrams of transmitter and receiver mathematical models.

lations) for subcarriers with a high signal-to-noise ratio (SNR) and fewer bits for subcarriers with low SNR (Fig. 4a). Given the channel state information, the transmitter deduces SNR for each subcarrier and chooses the best bit allocation scheme. The receiver understands the scheme applied from a bit allocation table, included in the frame's PHY preamble. Selecting such a table in runtime is protocol-specific and requires support from the MAC layer protocols.

The adaptive bit loading approach provides higher robustness in LC channels, even in the event of blocked LoS paths. In addition, adaptive bit loading improves throughput in mobile environments. To achieve even higher performance, adaptive bit loading can be accompanied by power loading that redistributes power subcarrier-wise. Figures 4b and 4c demonstrate that in a simulation [11], bit and power loading enable transmission at SNR below 4 dB and reduce SNR required for 100 Mb/s by up to 17 dB, compared to uniform bit and power allocation. The authors of [11] show that bit and power loading combined maintain the highest possible throughput in low-light and NLoS scenarios. Although adaptive bit loading can be potentially used for RF, its gain is too small for RF and cannot compensate for very high protocol complexity. In RF, the average channel quality (i.e., SNR) is almost the same for all tones, although the instant SNR may quickly vary because of fading. In contrast, in LC, the average SNR in wide LC channels decreases with frequency, as shown in Fig. 4a. Hence, using the adaptive bit loading in LC justifies its increased complexity compared to the uniform bit allocation.

TGbb has initially agreed to include both options in 802.11bb: the existing 802.11 PHYs and the LCO PHY. However, by July 2021, it had become apparent that the efforts required to incorporate LCO PHY are much higher than initially expected. Hence, TGbb decided to exclude it from the scope of 802.11bb and to postpone investigations of the LCO PHY as it remains promising for following versions of Li-Fi.

### Current Status

Draft 1.0 defines four LC PHYs: LC common mode PHY based on 802.11a and three high-throughput ones based on 802.11n, 11ac, and 11ax. All these PHYs can use channels in the range of 800 to 1000 nm. As stated in the legacy 802.11 standard, the devices supporting PHY of a specific generation are obligated to support PHYs of all previous generations as well.

The stations can use LC CM PHY for basic operations, such as initial association, parameters negotiation, and choosing another PHY for further data exchange. With LC CM PHY, transmissions occur only in the 20 MHz channels at low data rates of 802.11a (i.e., 6 to 54 Mb/s).

The LC variants of 802.11n/ac/ax PHYs can provide nominal data rates up to 150 Mb/s, 867 Mb/s, and 1200 Mb/s, respectively. They fully inherit the modulation and coding schemes and available bandwidths from the respective standards. These high throughput PHYs support using multiple transmit and receive chains, but using them differs from classical multiple-input multiple-output (MIMO), as discussed in detail in the next section.

## Medium Access Control Layer

In addition to PHY, 802.11bb amends MAC protocols with a few changes caused by the peculiarities of LC. TGbb considers critical issues related to the hidden stations and LoS blockage.

### Preventing the Hidden Stations Problem

A key MAC issue for free-space LC networks is the hidden node problem because the stations associated with the same AP may be hidden from each other. Using traditional carrier sense may result in many collisions in the uplink. TGbb has proposed an alternative: repetition clear channel assessment (RCCA). With RCCA, the AP retransmits any detected uplink signal using the amplify-and-forward approach. Thus, it informs all the associated stations that the channel is occupied. The stations only need to detect the channel as busy rather than fully decode the signal. The retransmission by the AP would lag for just a few nanoseconds, which is negligible compared to 802.11 timing. Figure 5a shows, in experiments with and without RCCA, that the throughput is twice as high during the intervals when RCCA is switched on [12]. It happens because RCCA reduces collisions caused by hidden nodes and PER (Fig. 5b).

To utilize RCCA, the AP needs to receive and retransmit the signal simultaneously. Due to self-interference, this scheme is inapplicable for RF but feasible for LC. The directional property of light allows performing simultaneous reception and retransmission unless the AP shines in its photodetector. If a client station experiences no self-interference, it can theoretically organize full-duplex communications with the AP. Such an operation would require significant changes to 802.11 MAC. For example, the specification would need to define the possible frame sequences and the rules for selecting the duration of a simultaneously transmitted frame. In addition, it shall be verified that such simultaneous transmission would not confuse other LC stations. A disadvantage of this new feature is its possible security violation: a potentially confidential transmission would be unintentionally broadcasted in the network. However, this problem can be fixed easily by allowing a user to control this setup in their LC APs.

In theory, RCCA can also be used for communication between two LC stations connected to the same AP if the direct signal transmission is difficult (e.g., due to the lack of LoS). AP would simply serve as an instant relay, forwarding the signals from communicating LC devices. We foresee a high potential of this idea, but it has yet to be developed in 802.11.

Another way of avoiding collision between hidden nodes is using the scheduled channel access method. A candidate solution is a scheme used in 802.11ad/ay, namely, contention-free service periods that are allocated by the AP.

### Tackling LoS Blockage

In wireless optical communication systems, LoS links often experience interruptions.

For example, if the optical detector is not directed at the intended light source, it leads to a sharp deterioration in signal quality. If an opaque object blocks the LoS path, it will likely break the connection.

The first possible solution is to use multiple spatially distributed transmitters and receivers so that simultaneous blocking of all connections becomes less likely. However, such a solution may cause unwanted interference between different transmitters.

Another solution is based on the alternating use of optical and radio links. If the LoS path is blocked, the devices switch to radio communication and vice versa. Efficient hybrid operability of LC and RF in 802.11 can be provided with the Fast Session Transfer mechanism.

This mechanism allows the device to operate in multiple frequency ranges alternately. It is already used by 802.11ad/ay devices working in the 60 GHz band and will be adapted for 802.11bb. The use of 802.11bb in combination with other technologies of the 802.11 family will support high mobility of users, increase network coverage, and speed up the process of link setup.

## Challenges and Open Issues

As we stated earlier, 802.11bb is considered to be the first step toward bringing high-rate LC to Wi-Fi: it introduces only basic functionality, while many potentially fruitful directions are postponed for future standards. Future standards may both improve the properties of LC itself and adapt promising features of other 802.11 standards (Table 1). One such feature is multi-link operation, which is currently under development as a part of 802.11be [13]. Although modern Wi-Fi chipsets can already use several links simultaneously, say 2.4 and 5 GHz, the links are fully independent, which limits the efficiency of such operation. For example, the current implementations do not allow to quickly balance the load between the links, duplicate the packets to achieve higher reliability, or concurrently access the channel to reduce channel access delays. 802.11be addresses this issue by allowing more flexible fragment and packet reassembly, dupli-

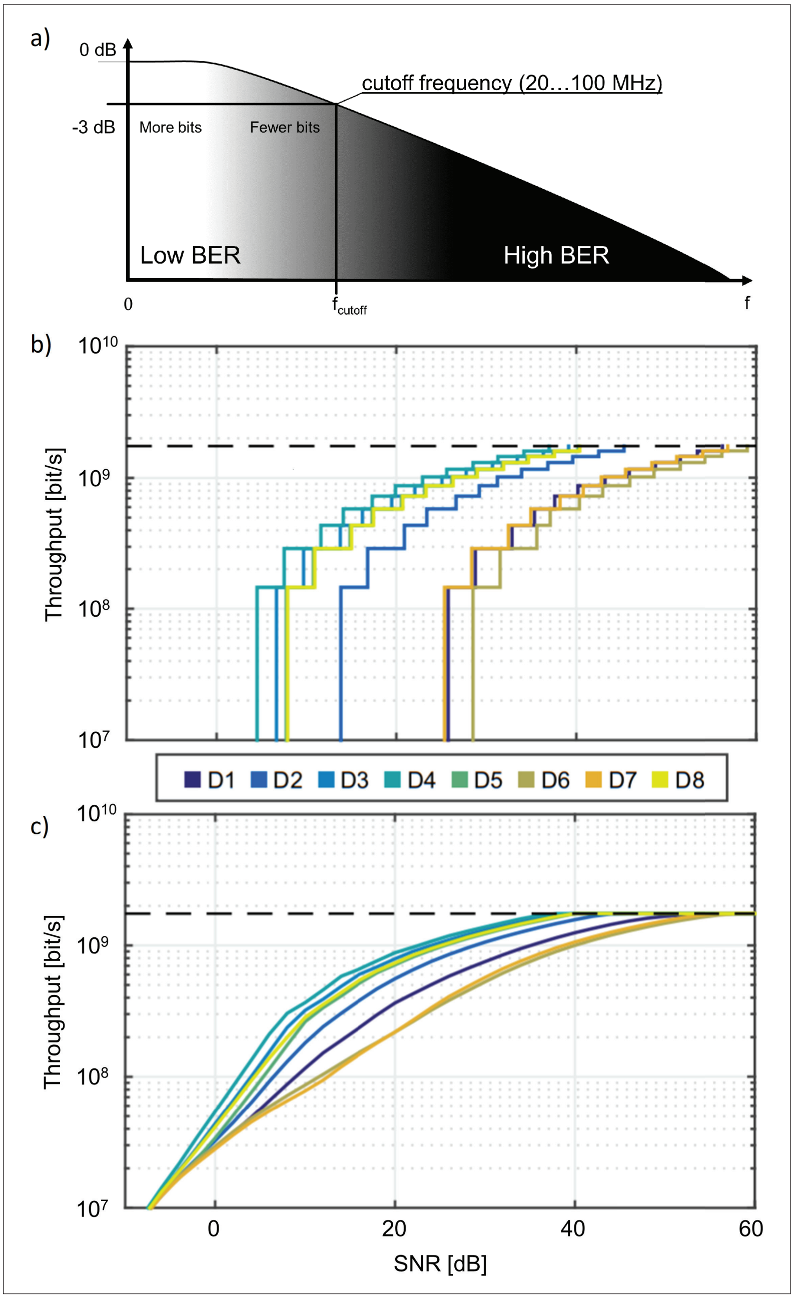


**Figure 4.** a) The first-order low-pass response of an LC channel; b) net throughputs for LEDs D1–D8 in the manufacturing cell scenario (802.15.7) with the use of a quasi-cyclic LDPC code, $R = 5/6$ with the same power and modulation for all subcarriers; c) bit and power loading (adapted from [11]).

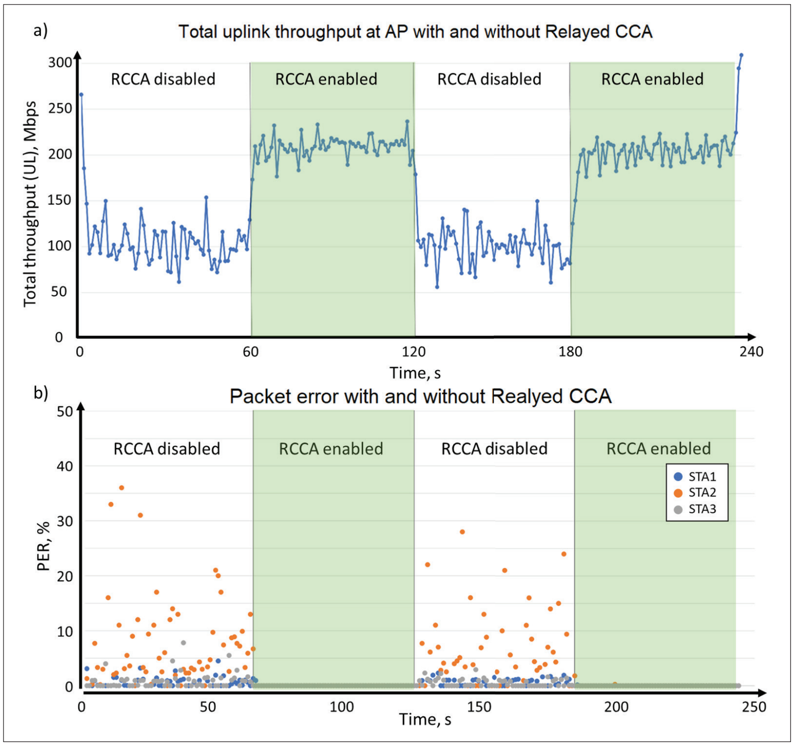


**FIGURE 5.** Experimental performance evaluation results of RCCA with three LC stations [12]: a) total uplink throughput at AP; b) packet error rate.

| | 802.11bb-D1.0 | Next generation LC beyond 802.11bb |
|---|---|---|
| PHY | LC adaptation for 802.11a/n/ac/ax (without beamforming) | LCO PHY [10] |
| | LC frontend [8] | Adaptive bit loading [11] |
| | LC adaptation for multiple spatial streams (without MIMO) | New sounding protocol for adaptive bit loading |
| | LC channelization [9] | Beamforming, (MU-)MIMO [14] |
| MAC | Inherited 802.11a/n/ac/ax | Full duplex operation [15] |
| | Inherited from 802.11ad Fast Session Transfer mechanism | Further channel access optimization (e.g., [15]) |
| | Repetition CCA [12] | Multi-link operation [13] |

**TABLE 1.** Summary of main IEEE 802.11bb and future Li-Fi features.

cation detection, and load balancing between the links. For example, packet retransmission may occur on any link regardless of the link where the initial packet was sent.

For LC, multi-link will allow concurrent communication using either multiple separated LEDs and photodetectors, or different parts of the LC spectrum (e.g., infrared, red, green, and blue bands). The latter case raises the issue of dividing the LC spectrum into these bands and designing LC frontends (LEDs and photodetectors) to work in the dedicated channels. Using off-the-shelf single-color LEDs and photodetectors may bring some interband interference, which shall be tackled. On the other hand, researchers can offer new recommendations or standards for manufacturing interference-free multi-link (multi-color) LC transmit and receive frontends.

The LC versions of 802.11 PHYs support using multiple transmit and receive chains, identical to the RF version of the PHYs. However, they do not support beamforming. The channel matrix is supposed to be diagonal for 802.11bb devices; that is, the transmitting chains need to be spatially separated to prevent cross-stream interference on the receiver side. But using spaced-out frontends seems impractical for mobile devices, so we expect this feature to be used rarely. On the other hand, using classical MIMO with a non-diagonal matrix is quite a challenge in Li-Fi. Because of the low carrier frequency and small spacing of LEDs and photodetectors, the channels between different light sources and a receiver are highly correlated, which causes an ill-conditioned channel and leads to poor MIMO performance. To solve this problem, light can be focused into beams for different users, but this approach requires a special transmit lens at the AP, and using separate non-interfering APs is considered more practical for 802.11bb. Alternatively, the receiving devices can be equipped with a lens that *images* the light sources on a photodetector array, thus separating the sources. Such imaging receivers [14] can enjoy spatial diversity gain but might require a large optical system. As MIMO has proved to be extremely fruitful for wireless communications, we believe that practical solutions will be further considered in future iterations of LC standardization.

The next challenge is LCO PHY development and adaptation. Although TGbb has postponed the related activities, LCO PHY remains promising, and more research on this topic is in great demand. One vital issue is the coexistence of LCO with other PHYs because the numerology of LCO PHY from ITU-T G.9991 is upclocked by 20 percent compared with 802.11, and channel widths do not coincide.

For interoperability (i.e., correct operation of carrier sense and clear channel assessment mechanisms), all PHYs need to detect and understand the preambles of each other. To address the issue, either an LCO PHY numerology should be changed, which reduces the nominal data rates by 20 percent, or devices supporting LCO PHY should use a fractional phase lock loop, for example, to generate a legacy preamble prepended to the frame with different bandwidth and subcarrier spacing. Fractional phase lock loop in mobile devices requires a higher sampling rate, increasing the power consumption and complicating the circuitry. Apart from being challenging itself, the LCO PHY protocol requires new MAC rules.

802.11bb Draft 1.0 fully reuses the RF PHYs without introducing new ones. This decision is perfect for shortening the development time, and it will target some use cases from earlier (e.g., operating in RF-restricted areas and providing security). However, the wide market requires ever higher throughput and lower delay. The light medium has a capacity hundreds of times greater than that of the unlicensed radio spectrum. Li-Fi can be a pathway to terabit communications in WLANs. We believe that to obtain a larger share in the market, the next LC standard beyond 802.11bb needs to introduce new technical solutions to boost the data rate.

As discussed earlier, LC potentially allows full-duplex operation, which requires redesigning the architecture and developing new MAC features. The progress of the Full-Duplex Technical

Interest Group (FD TIG) can be helpful. Although its main focus was on canceling self-interference in RF, which is not an issue for LC, some ideas can be taken from FD TIG results (e.g., the collision detection method [15]). If the AP can inform STAs about an ongoing collision, the stations can stop their transmissions, which greatly improves channel utilization, enhances long-term throughput, and provides support for real-time applications.

The postponed LCO PHY requires a new MAC protocol. For example, to use adaptive bit loading, the transmitter needs information about per-subcarrier SNR at the receiver. Hence, an implicit or explicit fine-grained sounding protocol is required. A procedure and frame content for sounding and explicit feedback need to be defined. A sounding procedure from 802.11 may be reused, but it still requires massive changes to fix the numerology mismatch.

An important problem that can be solved by academia is finding the optimal sounding period. If the channel is almost static, rare sounding can be enough, but in a dynamic channel, the devices need to update channel state information more frequently.

## Conclusion

When radio communications lack spectrum, LC becomes a savior. 802.11bb is a revolutionary amendment that introduces LC to the Wi-Fi ecosystem. In this article, we have analyzed the current state of the development process of 802.11bb, the standard for future Li-Fi, and related open issues.

802.11bb relies on the established 802.11 PHY and MAC framework, which will highly facilitate the integration of future Li-Fi technology to the mass market.

The developers of 802.11bb pay special attention to using Li-Fi in industrial, medical, enterprise, and residential environments. For these scenarios, TGbb describes usage models and derives the requirements for the technology. By providing a common evaluation methodology, channel models, and LC frontend models, TGbb shapes and directs further Li-Fi research and simplifies the development process.

We have reviewed the main PHY and MAC novelties of 802.11bb. Importantly, we have identified the open issues associated with the future Li-Fi standard. We have outlined some future features of LC specification that may be adopted in the next Li-Fi versions, such as LCO PHY, FD, and MIMO. In addition, the future LC standard will need new solutions that provide much higher throughput to meet the market expectations. These features, listed in Table 1, require much more work to be done by researchers and engineers. We believe that this work will attract the research community to 802.11bb challenges. Their contributions will improve LC technology with extensive studies and practical solutions.


## Acknowledgment

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The developers of 802.11bb pay special attention to using Li-Fi in industrial, medical, enterprise, and residential environments. For these scenarios, TGbb describes usage models and derives the requirements for the technology.