Long Range Low Power (LRLP) Wireless Network

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Abstract

A long range and low power wireless network refers to the ability of long distance communication associated with low power rate. Although the low power has been achieved in some systems but the long distance has not been achieved. It is hard to achieve the low power and long distance at the same time. In this paper, we discuss the applicability and limitations of existing long distance and low power technologies in the context of wireless network. First, we give an overview of the deployment model and general related works. We then present low power and long range works and highlight specific technical challenges encounter in wireless network.

Keywords

Long Range, Low Power, Power Management, Beamforming, TDMA, Antenna, Wi-Fi,

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1. Introduction

The development of LRLP wireless networks could play an important role in connecting a range of devices that need to be low mobility, low power and low cost. As part of the Internet of Things, these connections are likely to serve a diverse range of industries, such as automotive, utilities and health, and cover a range of applications and deployment scenarios in which mobile and short-range wireless network technologies may not be best placed to provide connectivity.

Recently, the LRLP protocols such as SIGFOX, Ingenu, and LoRa [margelis15] has emerged to fill the gap between local wireless and mobile wide area network technologies. These protocols possess several characteristics that make them particularly attractive for devices and applications that require low mobility and low data transfer. The introduction of LRLP protocols as fundamental for IoT applications promise to bring a number of basic advantages including: (i) longest range (ii) robust links (iii) extended battery life. Such features can support networks up to 7.4 billion connections by 2020 [lowpower15].

The concept of LRLP has been formulated to reduce energy consumption and increased the transmission distance at the same time. Researchers have proposed a variety of approaches to achieve either long range or low power. It was established that achieving these goals would require a coordinated power-optimization and power-transmission effort across every level of the design hierarchy (application, network, media access, physical layer, computation versus communication) and every single component of the node.

In the followings, related works pertaining long range and low power is discussed in Section 2. Long range and low power is explained in Section 3 and Section 4 respectively. Higher gain antennas and adapter placement is described in Section 5. Finally, conclusion is presented in Section 6.

2.0 Related Works

This section discusses the related works that has been carried out by several researchers such as power management mode, modulation and addressing, channel coding and beamforming.

2.1 Power Management Mode

In 802.11, two power management mode are specified: active mode a station continually turns on the radio components and power saving mode, a station alternates between awake state and doze state [saedy12]. Awake state can sense the incoming signal all the time and also transmit and receive signals. On the other hand, with power saving mode, the station in doze state turns off the radio components. Hence, it cannot sense incoming signals at all. When doze state received packets, the AP will buffer the packets until the station wakes up and requests the delivery of the buffered traffic. In 802.11 system, AP periodically transmits beacon frame, which contains Traffic Indication Map Indication Element (TIM IE). The partial virtual bitmap field in the TIM IE conveys the information of the existence of buffered traffic destined to power saving stations as shown in Figure 1.

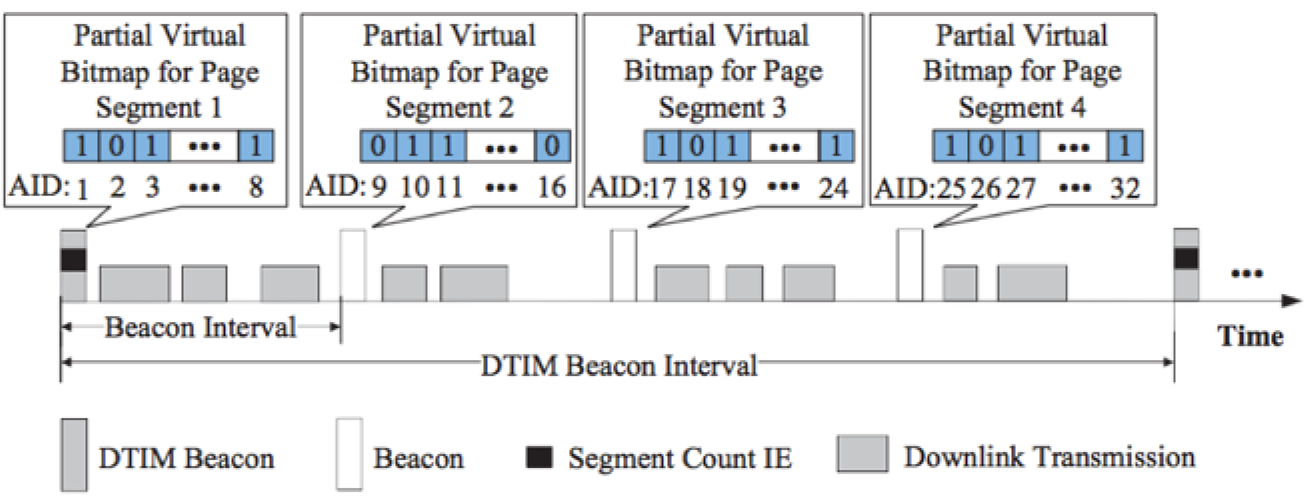


Figure 1: Diagram of page segmentation [saedy12]

A power saving station needs to wake up periodically to receive a beacon. If it recognizes the existence of buffered traffic, the station transmits a control frame called Power Saving (PS) poll frame to the AP to request the delivery of the buffered packets. After finishing the reception of the buffered packets, the power saving station can go back to doze state. However, due to a large number of stations in the network, several undesirable phenomena could happen such as the beacon frame could become extremely long. This is due to the excessive length of the partial virtual bitmap in TIM IE.

Moreover, if the amount of the buffered traffic is too heavy to be accommodated within a beacon interval, some power saving stations stay in awake state to complete the receptions of their buffered packets. 802.11ah applies a mechanism call TIM and page segmentation. More specifically, as stated in [saedy12] :

- An AP splits the whole partial virtual bitmap corresponding to one page into multiple page segments.
- Each power saving station wakes up at the transmission time of the beacon which carries the buffering information of the segments it belongs to.
- A new IE called segment count IE is defined to deliver segmentation information, such as the resulting number of segments after page segmentation and the boundary of each page segment.
- DTIM beacon is a beacon frame that includes Delivery TIM (DTIM) IE. It used to indicate the buffering status of group addressed packets.
- The segment count IE is contained in every DTIM beacon which is transmitted periodically over several beacon intervals to save power.

2.2 Modulation and Addressing

The improvement of Packet Error Rate (PER) of WuRs have been extensively studied [matyjas15]. Some works on modulation techniques considering pulse width modulation (PWM) [matern10] and pulse position modulation (PPM) [chen14], while other studies investigate address-coding scheme [gante14]. However, none of these achieve maximum modulation gain and increase the power consumption by the longer wake-up sequences of 31 and 48 bits to maintain a probability of detection of 90% [liu14].

In [liu14], the address-coding scheme used probabilities of detection (Pdet) of 90% by increasing the bits of the wake-up sequence. The wake-up sequence consists of a pseudo-noise (PN) code sequence of length N. The PN code supports low correlation with other sequences, which avoids a false alarm (FA) from other communicating nodes or wake-up signals for neighbor nodes. For constant Pdet of 90%, the authors had adjusted the correlated threshold and RF input power level. If N is 31 bits, the mean time between FAs is about 10s at the given RF input power of −56 dBm and a constant. Similarly, if N is seven or 15 bits, the mean time between FAs is about 0.1 s. As a results, increasing the bits of the wake-up sequence reduces FAs in a certain time.

2.3 Channel Coding

In the context of channel coding, some existing studies propose a variety of channel coding and forward error correction (FEC) methods to improve bit error rate (BER) and PER for wireless and optical communication. Work from Proakis et al. [proakis10], proposed the used of Hadamard codes to improve the probability of bit error over block orthogonal code on a Rayleigh fading channel with a bandwidth constraint. The Hadamard code achieves better performance than the block orthogonal code.

Two types of optical orthogonal code (OOC) for synchronous and asynchronous incoherent optical CDMA (OCDMA) mentioned in [arikan10]. In [kudekar11], claim that proposed OOC scales well with the number of users. From their analysis, a specific length of orthogonal codes conducted by the author provides an error correction scheme without bandwidth expansion by partitioning data into blocks at the expense of complexity. Then, they later proposed orthogonal on-off keying (OOOK) for free-space laser communication. A block of data is mapped into a block of bi-orthogonal code, which provides the error correction capability through a correlation process. These designs do not consider the sensitivity, power consumption and latency. Work in [richardson01] find increased interference rejection capability for channels with multiple access or multipath interference.

2.4 Beamforming

Several studies have been proposed to optimize beamforming vectors and power configurations [wong10] for improvement of the information and energy transfer. Transmit beamforming (Tx BF) is vital technique implemented in digital signal processing (DSP) logic to improve range and data rate. Tx BF works on the principle that signals sent on separate antennas can be coordinated to combine constructively at the receive antenna. In Tx BF transmission, the phases of the transmit signals are manipulated to improve directivity.

Tx BF is specified in the IEEE 802.11n specification and takes advantage of the multiple transmit antennas available in a multiple input, multiple output (MIMO) system [palomar03]. To achieve efficiency of each streams, transmit diversity with a known channel is required through knowledge of the channel between the transmitter and receiver.

In 802.11, an AP beamforms to the client and provides increased gain at the client [palomar03]. This leads to higher data rates and reduced number of retries, which in turn can increase the overall capacity of the system and lead to more efficient use of the spectrum. The range improvement can be up to twice without beamforming and the gain improvement can be up to 12dB. As the number of transmit antennas is different from the number of receive antennas, Tx BF provides maximum benefit in an asymmetrical system.

3.0 Low Power Wireless Network

Power consumption becomes an important consideration at the location that is difficult to wire. The major issue arises from device batteries that need to be recharged frequently. So remote network nodes will often need to be self-powered, and frequent battery changes would be undesirable. Since wireless network consume a lot of power, one way to conserve power is to place some intelligence in the edge nodes themselves so that they will know when to talk, listen, or sleep.

3.1 IEEE 802.11 Low Power

Low Power in IEE 802.11 can be achieved through multi-hop routing [bartolli11]. It ensures that packets from a source are forwarded to the sink where processing takes place. The authors consider connectivity and load-balancing to ensure network reliability and performance. They investigate how packet forwarding tasks are distributed among the nodes in order to identify the hotspots. Their findings demonstrate network parameters when deploying low-power wireless networks. The authors also provide new routing protocols with further improved network reliability, reduced delay and increased energy efficiency.

There are several works on low power wireless network. In [fahrion11], the authors consider that Time Slotted Channel Hopping (TSCH) divides time into slots, and maps timeslots to channels with a pre-assigned hopping sequence. Every packet is scheduled and synchronized for energy efficiency with no extra preamble (Tx side) or guard interval time (Rx side). Low power mesh networks can also use techniques like Message Queue Telemetry Transport (MQTT), an open source, lightweight publish/subscribe messaging protocol. For instance, protocols like HTTP and MQTT can minimizes bandwidth and power needs by enabling a publish/subscribe messaging model.

3.2 Low Power Consumption Challenge

One of the great challenges of wireless communication is the reliability. It is important to understand the sources of unreliability to be able to account for them in communication systems. In low power wireless networks, the main sources of unreliability are external interference and multipath fading. Interference occurs when an external signal (e.g., Wi-Fi) temporarily prevents two radios from communicating.

The process of retransmission consumes more power. When a wireless signal bounces off objects in the vicinity of the transmitter, multipath fading might occur and consequently the various echoes destructively interfere at the receiver’s antenna. Such an occurrence is a function of the environment, position of the devices, the frequency used. A single RF frequency channel will experience problems over the operational life of a wireless system because the surrounding environment of any wireless system.

Since multipath fading is frequency dependent, one frequency may be experiencing a problem, while several other RF frequency channels work well. The solution of interference and multipath fading is by employing channel and path diversity without sacrificing low power operation.

3.3 Wi-Fi Power Savings

Power saving cognitive wireless LANs can be used with combination of solar panel, wind turbine and battery [srinivasan10]. The autonomous wireless network can be established and provide normal network functionality even through the other wired electric power and network are seriously damaged. The main conclusion drawn from this work is that with multiple LANs with different transmission characteristics such as IEEE802.11b,g,j,n, IEEE802.16, can be provided even though the communication environment has been changed.

By using combination of fixed and mobile cognitive networks, a large disaster communication network can be organized. A communication path between nodes has multiple links. The suitable links among them is selected based on the distance, power and transmission frequency. User can communicate with other user and send/receive disaster information even though some of information infrastructure are damaged by multi-hopping those nodes. Table 1 below shows the comparison of various energy sources.

Table 1: A Comparison of Energy Sources [rabaey14]

Table 1. A comparison of energy sources.

Energy source	Power density	Energy density
Batteries (zinc-air)		1050 -1560 mWh/cm³
Batteries (rechargeable lithium)		300 mWh/cm³ (3 - 4 V)
Solar (outdoors)	15 mW/cm² (direct sun) 0.15mW/cm² (cloudy day)	
Solar (indoors)	0.006 mW/cm² (standard office desk) 0.57 mW/cm² (< 60W desk lamp)	
Vibrations	0.01 - 0.1 mW/cm³	
Acoustic noise	3E-6 mW/cm² at 75 Db 9.6E-4 mW/cm² at 100 Db	
Passive human-powered systems	1.8 mW (shoe inserts)	
Nuclear reaction	80 mW/cm³ 1E6 mWh/cm³	

*Values are estimates taken from literature, analyses, and a few experiments.

**Values are highly dependent on the amplitude and frequency of the driving vibrations.

3.4 Energy Efficient Network

Several companies have developed application or products specific integrated circuits that are optimized for sensing applications. These products achieve low power architectures whilst leveraging the huge installed base of over 2 billion Wi-Fi certified devices. Ozmo devices one among of the first companies promoting the concept of low power Wi-Fi [clarke15]. To achieve low power Wi-Fi, the researchers tune the .11 protocol stack and introduce aggressive power saving operations.

High transmission power drains batteries in mobile devices. The number of devices that are battery dependent is growing such as mobile phones, netbooks and many and they are connected to indoor wireless networks. The power consumption of an 802.11 chipset reported in is 400 mW when transmitting at 100 mW and 45mW in power-saving mode. Battery lifetime is a critical design constraint in many wireless networking applications since many wireless nodes are typically battery operated and need to operate for months or years without maintenance. Optimizing battery life, however, requires that developers look beyond the efficiency of the transceiver. Operating life for a sensor node also depends on the node's range, radio sensitivity, data rate and the number of nodes in the network.

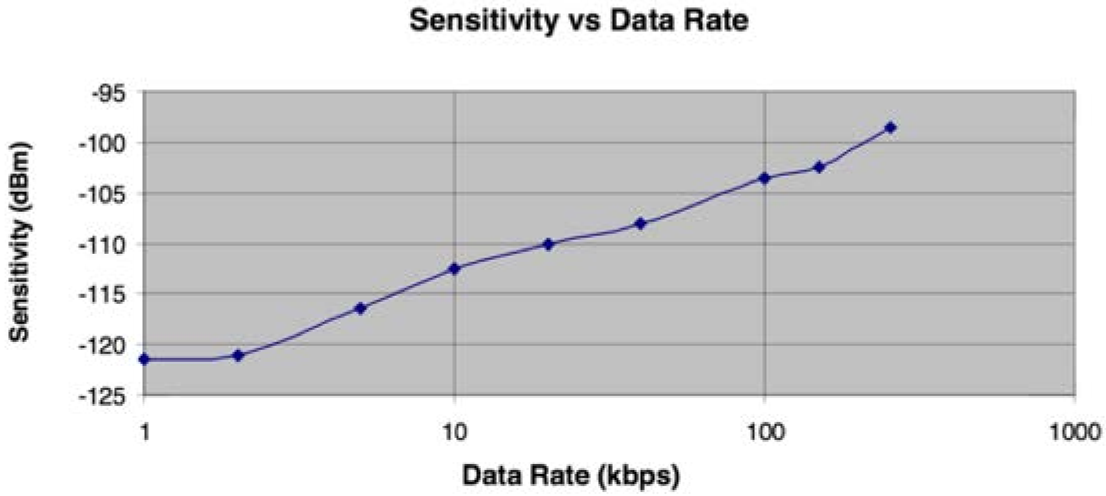


Figure 2 : Sensitivity Increases with lower data rates [silicon15]

In [silicon15], range is determined by the sensitivity of the transceiver and its output power, commonly referred to as link budget. The authors conclude that a primary factor affecting radio sensitivity is the data rate. The lower the data rate, the narrower the receive bandwidth is and the greater the sensitivity of the radio (figure 2). The author also points out that sub-GHz radios are able to support a narrower channel bandwidth than 2.4 GHz radios. For many sub-GHz applications, range is the most important design constraint. Increasing the transmit output power extends the range and coverage but consumers more battery power. According to[vangelista15], as the range increases, it can result in lower system cost. The fewer nodes need to be in the system to provide complete coverage of an area.

Table 2: Summary of Key Factors between Sub-Ghz and 2.4 Ghz solutions [silicon15]

Key Factor	Strength	Comments
Range	Sub-GHz	Higher regulatory output power, reduced absorption, less spectral pollution, narrowband operation.
Power consumption	Sub-GHz	Better circuit efficiency, improved propagation at sub-GHz. 2.4 GHz chips performance much lower.
Software cost	Proprietary	Small stack sizes, targeted applications.
Multi-vendor	Sub-GHz 2.4 GHz	Most standards are at 2.4GHz (due to global frequency); Many sub-GHz standards are also available.
Worldwide deployment	2.4 GHz 433 MHz	2.4 GHz has an advantage. 433 MHz can be used in most of world except Japan. Same 868 MHz/915MHz designs for most of world.
Antenna size	2.4 GHz	Smaller antennas optimal with 2.4 GHz; however very small designs can be achieved in sub-GHz.
Data rate	2.4 GHz	Much higher throughput can be achieved.

3.5 Modelling Low Power Wireless Network

The low power wireless communication can affect the performance of wireless protocols such as flooding, and opportunistic routing. Most existing works have been made toward establishing an effective directly measure link correlation using packet level transmission and receptions [radi14]. Measurement is insufficient because it lacks predictive power and scalability. One of the proposed models is CorModel, a model for predicting link correlation in low power wireless networks [wen15]. The authors investigate four easily measurable parameters for the model, such as received signal strengths at multiple receivers, noise and interference, the packet length, and the packet transmission interval. Based on these parameters, they develop a model for predicting wireless link correlation.

Based on the experiment, network layer parameters have significant impact on link correlation. The authors validate the model and illustrate its usefulness by integrating it into existing protocol for more accurate correlation estimation. As a result, their model can significantly increase the accuracy of wireless link estimation, resulting in better protocol performance.

Moreover, authors in [wen15] observe that the packet rate affects the power consumption at a given beacon interval. Their role is to shows a relationship between power consumption and packet rate with short data packets of 34 bytes and long data packets of 2334 bytes, respectively. The beacon interval is set to 100 ms. The conventional MAC protocol incurs a higher power consumption than their MAC protocol (notated as WuR). This is because of the conventional MAC protocol has idle-listening on high-power Wi-Fi radio. The packet rate can affects the power consumption at a given beacon interval as shown in Figure 3.

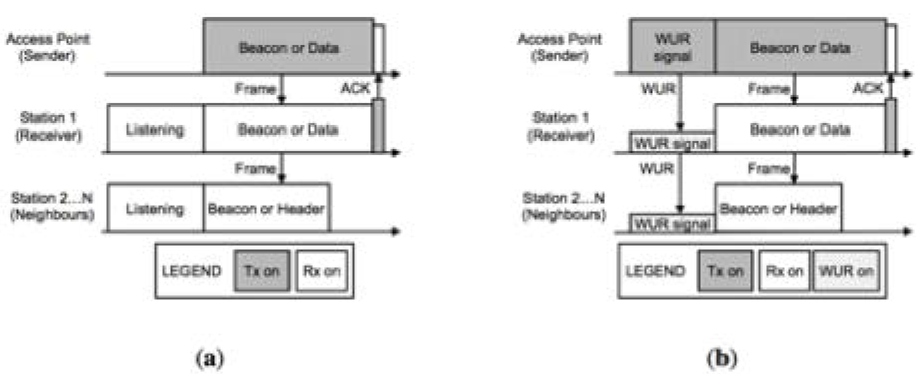


Figure 3 : Comparison of the proposed MAC protocol with a conventional MAC protocol. (a) Conventional MAC protocol (b) Proposed MAC protocol [wen15]

In addition, authors work shows that MAC protocol takes advantage of their LDWuR to save listening power. The long data packet gains higher power consumption than the short data packet, as the high-power Wi-Fi radio transmits a longer data packet from the AP to the station.

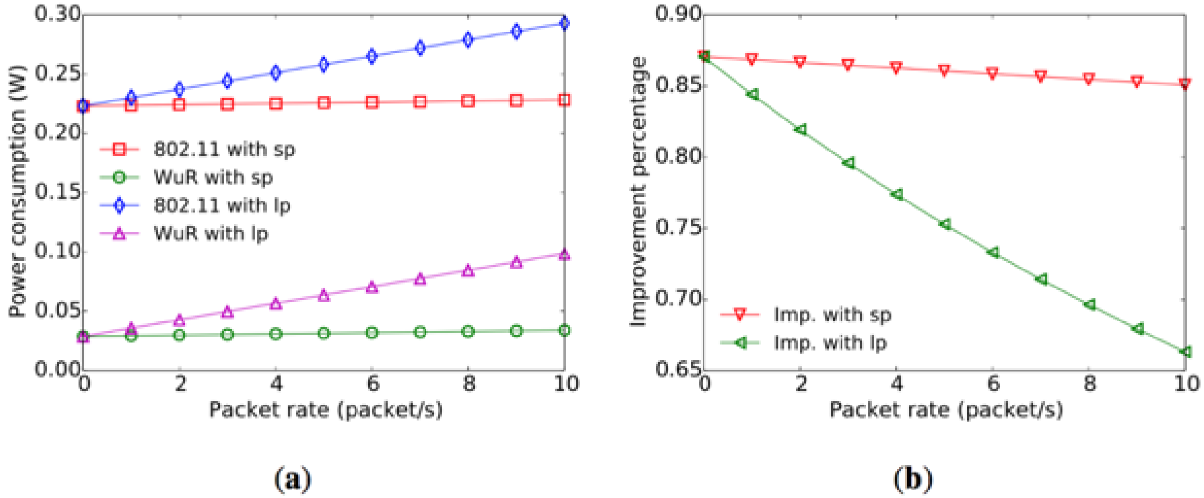
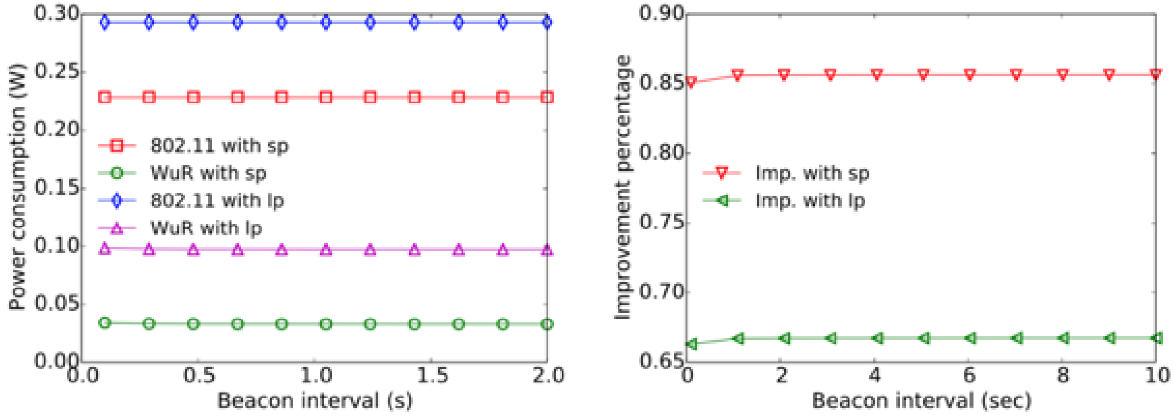


Figure 4 : Power consumption is a function of packet rate (a) Power consumption versus packet rate (b) improvement of power consumption versus packet rate [wen15]

Figure 4 above shows a relationship between power consumption is a function of packet rate. In terms of a short data packet, the improvement percentage decreases slightly when the packet rate increases, as MAC protocol has more wake up signal activity before beacons and data packets. For the long data packet, the improvement percentage decreases sharply when the packet rate increases. This is contributed as the high-power Wi-Fi radio deals with a long data packet that causes MAC protocol's power consumption to be closer to the conventional MAC protocol.

On the other hand, the affect of beacon interval on power consumption at a given packet rate has been investigated. It is proven that a small beacon interval has a slightly higher power consumption then a large beacon interval. A small beacon interval has more beacon activity in a certain time period and has lower improvement (see Figure 5). As the short data packet takes advantage of fewer activities on high power Wi-Fi radio, it provides higher improvement than the longer data packet.



(a) (b)

Figure 5 : Power consumption is a function of beacon interval (a) Power consumption versus beacon interval (b) improvement of power consumption versus packet rate [wen15]

4.0 Long Range Wireless Network

Radio waves propagate through space using the in verse square law. This means as the distance doubles the signal reduces by 75% [mindspeed14]. Range is determined by transmitter power in dB, plus receiver gain in dB, minus losses. The IEEE 802.11ah WLAN protocol amendment is a future outdoor long-range WLANs, which operate at the sub-1 GHz (S1G) industrial, scientific and medical (ISM) radio-band [okvist11]. A WLANs in outdoor locations is important, but many limitations of the usability of WLANs have been reported in the research literature.

4.1 Long-range IoT Communications Systems in Unlicensed Bands

4.1.1 Sigfox

Sigfox represent the most emerging leaders in low throughput networks (LTNs) and one of the main contributors of ETSI's efforts to create a relevant standard [sigfox15]. Sigfox offers high bandwidth, low jitter and high throughput which allows a variation of the cellular network. The advantages of the cellular network such as long range, wide area, easier to set up than managing smaller range networks are combined with lower power consumption, and lower cost. The Sigfox network provides connectivity for a variety of applications and users. The Sigfox network performance can be characterised by the following [margelis15]:

- Up to 140 messages per object per day
- Payload size for each message is 12 bytes
- Wireless throughput up to 100 bits per second

4.1.2 LoRaWAN

LoRaWAN is a Low Power Wide Area Network (LPWAN) specification intended for wireless battery operated in regional, national or global network [lorawan15]. It uses sub-GHz, unlicensed frequency bands and are characterized by long-range radio links and star topologies. The main requirements are secure bidirectional communication, mobility and localization services. LoRaWAN network architecture is a star of stars topology in which gateways is a transparent bridge relaying messages between end-devices and a central network server in the backend. Gateways are connected to the network server via standard IP connections while end-devices use single-hop wireless communication to one or many gateways. All end-point communication is generally bi-directional, but also supports operation such as multicast enabling software upgrade over the air or other mass distribution messages . Power consumption is proportional to the time devices spend listening. Therefore, the correct configuration of an end-point depends of the longevity expectations of the device as well as expectations for real-time downlink capabilities. Activation of the devices can be categorised in two which is either over the air or activation by personalization [margelis15].

4.2 Outdoor Long-Range WLANs

IEEE 802.11ah is a Wireless LAN (WLAN) standard that defines a WLAN system operating at sub 1 GHz license-exempt bands [prasad15]. It can provide much improved transmission range compared with the conventional 802.11 WLANs operating at 2.4 GHz and 5 GHz bands. 802.11ah can be used for various purposes including large scale sensor networks, extended range hotspot, and outdoor Wi-Fi for cellular traffic offloading, whereas the available bandwidth is relatively narrow.

The authors in [vaz10] describe channelization and transmission modes for 802.11ah. 802.11ah MAC layer has adopted some enhancements to fulfill the expected system requirements. These enhancements include the improvement of power saving features, support of large number of stations, efficient medium access mechanisms and throughput enhancements by greater compactness of various frame formats.

In addition, work in [matrakidis11] discussed a large capacity long distance wireless millimeter-wave (mm wave) signal delivery at W-band based on some enabling technologies and advanced devices. The authors have demonstrated 1.7-km wireless delivery of 20-Gb/s polarization division multiplexing quadrature phase shift keying (PDM-QPSK) signal at W-band. They also demonstrated 300-m wireless delivery of 80-Gb/s PDM-QPSK signal at W-band. Table 3 show summary works by researchers on outdoor long-range WLANS.

Table 3 : Summary on outdoor long-range WLANs [prasad15]

Testbed	Basis	Location	Antenna	Link distance	Prerequisites	Observations & Hypothesis
Sheth [54]	IEEE 802.11b (1 Mbps), 20-50 m antenna height, UDP 1440 B, 1 Mbps and 11 Mbps CBR.	Urban, rural	High-gain directional antenna (24 dBi, 8 degree beam-width), LOS.	2-20 km	MAC-layer ACKs disabled, retry=0; channel characteristics without retries.	Cause of packet loss for directional antennae is external WLAN interference. Remedies are *channel selection*, *ARF*, and *FEC* [73]. Ill-suited MAC protocol due to CSMA breakdown for long-range WLANs.
Afanasyev, *Google Wi-Fi* [56]	IEEE 802.11g	Urban, citywide	Directional antennae	500 m	None reported.	Rate-limited traffic per user is 1 Mbps. Hierarchically clustered to mitigate collisions at the AP induced by near users.
Aguayo, *Roofnet* [53]	IEEE 802.11b, multi-hop, wireless mesh network.	Urban	Omni-directional	>1 km	None reported.	Cause for packet loss is multi-path effects due to omni-directional antennae.
Bianchi [60]	IEEE 802.11b (1, 11 Mbps), IEEE 802.11g (6, 12 Mbps), point-to-point links, 8-15 m antenna height, EIRP=20 dBm.	Campus	Omni-directional, 5 dBi gain.	100-250 m	ICMP (1500 B) echo reply disabled to avoid reverse traffic. ARF, RTS/CTS disabled, retry=11. Fixed sending rate selected.	Poor IEEE 802.11g "multipath tolerance" compared to IEEE 802.11b due to short PLCP preamble. The ERP-OFDM training preamble is 16 μs (IEEE 802.11g), and 144 μs (IEEE 802.11b). PHY error dominates CRC errors (IEEE 802.11g).
Chebrolu [58]	IEEE 802.11b; 15-40 m antenna height; 0-20 dBm; 1 Mbps, 2 Mbps, 5.5 Mbps, and 11 Mbps; 100, 500, 1400 B; UDP & TCP.	Rural	High-gain directional parabolic grid antennae, 24 dBi gain, 8 degree beam width; sector antenna, 17 dBi gain, 90 degree beam width; 12 dBi antenna, 60 degree beam width.	1-37 km	MAC ACK disabled to measure the packet error rate independently.	Error rate independent of link length. No effect of weather conditions. *Near-field* effect and *RF leakage* are significant. Hardware performance limitations due to inefficient buffer interrupt process. Semi-legal countermeasures against mutual interference.
Sayed [55]	IEEE 802.11g	Desert	Build-in (directional) panel antenna; 24 dBi gain (AP); 30 degree beam width (AP); 18 dBi gain (STA); 28 degree beam width (STA); 3 m antenna height; 255 mW sending power (t_x, r_x).	<10 km	None reported.	Multipath interference is cause for packet loss due to omni-directional antennae.
Raman [67]	IEEE 802.11b, 0-20 dBm sending power.	Village	Parabolic grid directional antenna, 24 dBi antenna gain 30-40 m antenna height.	0.9 km-8 km	MAC ACK disabled; carrier sense disabled. Disable carrier-sense scheme (sensing of the noise-floor only). Send of dummy packets to maintain synchrony.	Side-lobes of near-proximity antennae, which do not allow concurrent transmission and reception of data frames. Near-field effect not mitigated even with high-precision antennae.
Bernardi [75]	IEEE 802.11b/g; f_c=2.4 GHz (access); IEEE 802.11a; f_c=5 GHz (backhaul).	Rural, coastal	High performance dish antenna (backhaul); 29 dBi gain; dual polarity; panel antenna (access); 19 dBi gain; rooftop mounted.	2.5 km to 19 km	Backhaul is configured to use ad-hoc demo mode to avoid sending management frames or beacons; RTS/CTS off; MAC Ack and slot time configured to support long-distance; ARF enabled.	Use of bidirectional backhaul links with different polarization to mitigate interference. Self-powered (wind/solar) WLAN APs.

4.3 Obstacles to long-range Wi-Fi

Although 802.1ah provides longer transmission range, it does not consider many practical issues. For example, it does not consider signal propagation. As mentioned in [vaz10], we need to consider some problems in Wi-Fi including :

- **Landscape Interference:** The obstacles such as trees and forests attenuate the microwave signal, and hills make it difficult to establish LOS propagation. In a city, buildings will impact integrity, speed and also connectivity. Steel frames partly reflect radio signals, and concrete or plaster walls absorb microwave signals significantly. Sheet metal in walls or roofs may interfere Wi-Fi signals, causing signal loss or multipath problems (as shown in Figure 6).

- **Tidal Fading:** Multipath interference from reflections over tidal water can be destructive. Multipath interference is a phenomenon in the physics of waves whereby a wave from a source travels to a detector via two or more paths and, under the right condition, the two or more components of the wave interfere (as shown in Figure 7).
- **GHz interference:** The transmission that dominate the 2.4 GHz can cause the noise floor. There are many other sources of interference that aggregate into a formidable obstacle to enabling long range use in occupied areas. Microwave oven, TV remote controller, wireless cameras, and Bluetooth products are all capable of transmitting in the 2.4 GHz band.

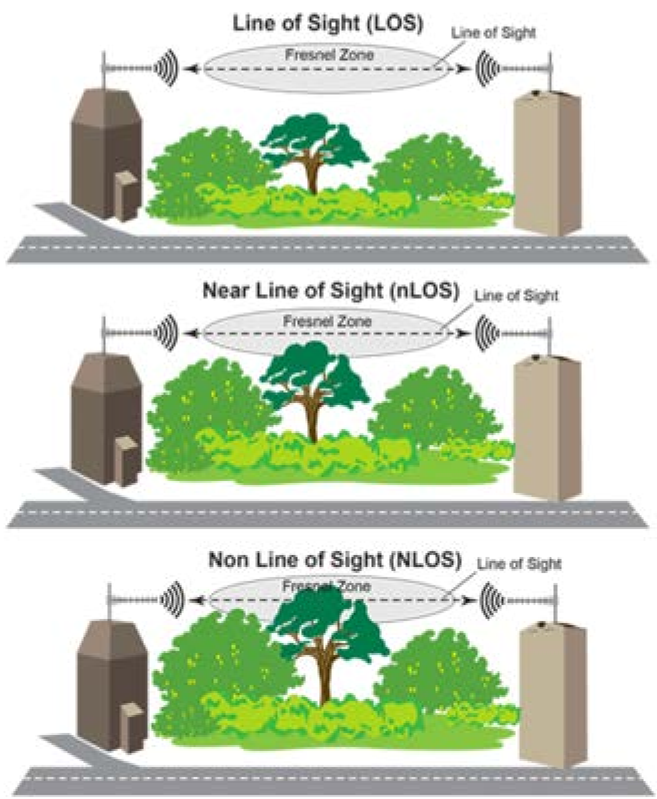


Figure 6 : Line of Sight propagation [antenna15]

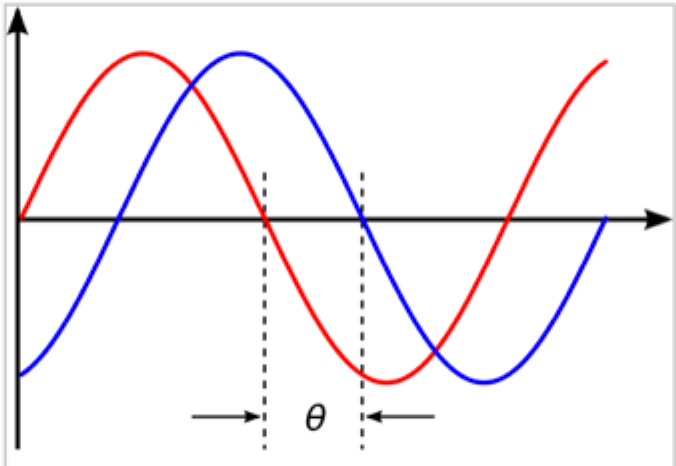


Figure 7 : Coherent waves that travel along two different paths will arrive with phase shift, hence interfering with each other [multipath15]

4.4 Improving Performance with TDMA

The Wi-Fi MAC has been modified to suit with long distance applications by replacing the CSMA Media Access Control with TDMA. It is better suited for long distance point-to-point links since it does not require the reception of ACKs. This can eliminate the wait of 2 ms round trip propagation time on a 300 km path [halasz10]. A research in [flickenger08], used commercial 30 dBi antennas, and also a couple of wireless routers which had been modified by the Technology and Infrastructure for Emerging Regions (TIER) group led by Dr. Eric Brewer of Berkeley University. In the experiment, they installed one of the antennas at the El Aguila site. A second team installed the other antenna at El Baúl. A solid link was quickly established using the Linksys WRT54G routers. This allowed for video transmission at a measured throughput of 65 kbps. With the TDMA routers, the measured throughput was 3 Mbps in each direction. This produced the total of 6 Mbps as predicted by simulations done at Berkeley. In addition, Halasz et al. [halasz10] suggested that TDMA schemes are beneficial in long-range WLANs, but should not be applied in mesh-networks.

4.5 Wireless coverage in rural and urban environments

There is a difference in regard to wireless coverage in rural and urban environments. Implementing the APs of a WLAN mesh in rural areas is tedious since it does not provide continuous coverage. This is because of the locations are primarily beside streets, harbors, and rivers.

The authors in [stefan15] reported that a maximum coverage of IEEE 802.11n with 4 spatial streams (SS) can reach up to 800 m at 50 Mbps with the use of directional antennae of 15 dB gain. The use of an antenna with 3 dB gain only lead to coverage of 400 m at 50 Mbps, which is appropriate for access links for mobile users. Some studies in [abuali12], [aust12] indicated that there is no direct correlation between the SNR value and the link quality. This is in contrast to the observations that the error rate behaves as a function of the received signal strength in a manner that is closely described by the theory [zhou13]. In [stefan15] reported on WLAN networks which target a coverage range of up to 3 km.

Coverage simulations of outdoor Wi-Fi hotspots with omnidirectional antenna were reported in [hamid11], which has been proven with experimental results. In fact, antenna heights, distance, and prerequisites are important indicators to compare the transmission performance of each outdoor WLAN.

5.0 Higher gain antennas and adapter placement

The first crucial step to build a wireless network is choosing the correct antenna for the application. Hence, coverage and range will be the driving factors. As figure 8 shows, antenna size and frequency are inversely proportional. There are several styles of Wi-Fi antennas with different radiation patterns, polarization schemes, and mounting options.

$$Length(cm) = \frac{7500}{freq(Hz)}$$

Frequency	Antenna Size
433 MHz	~ 17.3 cm (6.8 inches)
915 MHz	~ 8.2 cm (3.2 inches)
2.4 GHz	~ 3 cm (1.2 inches)

Figure 8 : Antenna size and frequency are inversely proportional [silicon15].

5.1 Long Range Wi-Fi Antenna

The low carrier frequency, low transmit power and full-duplex in a single band are alway used in indoor wireless. Several performance aspects of such a network have been conducted in [gharavo10]. The experiment result demonstrated that it can both match the connectivity of an equivalent Wi-Fi network and give superior performance. For that, the authors have proposed two techniques that enables full duplex communication.

Wi-Fi has proved to be cost effective for long distance applications. The two major limitations for using Wi-Fi over long distances which require LOS between the endpoints and vulnerable to interference in the unlicensed band. The first limitation can be addressed by taking advantage of the terrain elevations, or by using towers to overcome obstacles and provide Fresnel zone clearance. The second limitation is less pronounced in rural areas, and can be reduced by switching to the less crowded 5 GHz band.

All of the above studies can be overcome with power budget limitations and timing limitations when applying Wi-Fi to long distance. The first is easily solved by using high gain directional antennas, while the timing issue can be addressed by modifying the media access mechanism, as done by the TIER group at the University of Berkeley [flickenger08].

5.2 Antenna Design

Currently highly directive antennas on the market can range from as little as fifty dollars to a couple of hundreds of dollars. The gain of these antennas is between the ranges between 8dBi to 20dBi. To reach long range Wi-Fi, we need long range antenna technology. Specially shaped antennas, such as the Yagi antenna, can be used to increase the range of a Wi-Fi transmission without a drastic increase in transmission power [yagi15]. Implementing high gain antenna allow transmitting a narrow signal beam over distances of several kilometers, often nulling out nearby interference sources. Obstacles regarded as major problems when setting up a long-range Wi-Fi. Trees and forests degrade the microwave signal, and rolling hills make it difficult to establish LOS propagation.

The Raptor Wi-Fi antenna can prevent transmission signal loss due to obstacles such as trees and vegetation [gharavo10]. It was design with a removable antenna with a standard SMA antenna mount for connecting other antennas. Using a High Gain Yagi such as the 16dBi ANT001 Raptor Wi-Fi antenna, it need to point the antenna in the direction of the Wi-Fi Access Point. Considering higher gain antennas such as antenna ANT003, 9dBi OMNI antenna, it is best practice to place the Wi-Fi Access Point as high as possible.

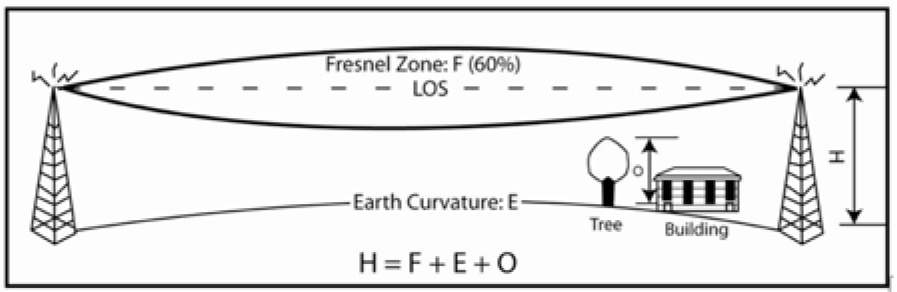
5.3 Antenna Installation

The researchers suggest using polarized antenna to further increase the diversity gain, such as in MIMO systems when using directional antenna [mimo13]. This approach has been found to be beneficial when path loss orthogonally cannot be achieved over long distances, even in a LOS situation. It is learnt that antenna configuration and the antenna null beam are affecting the transmission. A horizontal antenna configuration is recommended for narrow range while a vertical antenna configuration for wide range. The distances can be improved significantly by swapping the standard omnidirectional antennas with directional antennas.

A matched pair of APs with directional antennas, a network ‘bridge’ spanning between 1.2 miles to 2.4 miles, can be easily created at the places with many obstacles such as rivers, or in place of traditional infrastructure where the cost to install is prohibitive [antenna15]. For example, traditional LAN activities such as shared file, email, web access and voice over IP, can be transmitted over great distances at a very low cost. Furthermore, wireless links using 2.4GHz equipment and dish antennas have achieved distances up to 31 miles.

In a view of antenna height, the correct installation height of an antenna depends on the factors as outlined below [wifi15]:

- **Distance between the sites:** The longer the link, the higher the antenna needs to be due to the earth's curvature.
- **The Fresnel Zone:** 60% of Fresnel Zone values (accepted clearing on path). Add this to the earth curvature height (Refer to Figure 9).
- **Objects in the path:** A clear LOS at a frequency 2.4 GHZ.



Wireless Link Distance (Miles)	Value Fresnel Zone F (60% at 2.4 GHz.) Approx. Value	Value E (Earth Curvature) Approx. Value	Antenna Height H Antenna Height No Obstruction
1	2	3	4
3	23	4	27
5	30	5	35
8	40	8	48
10	44	13	57
15	55	28	83
20	65	50	115
25	72	78	150

Figure 9 : Three condition that make up LOS [antenna15]

Tree tops can deflect and absorb some of the signal. The theory is that the height of the tallest object in the path of the signal should be added to the Fresnel Zone and earth curvature clearance heights. It is important to check the height of the trees, hills, buildings or any object on the link path and add this to the measurement for the total of the tower height. There are three main categories of LOS, the first being full LOS where no obstacles reside between the two antennas. Non Line of Sight (NLOS) where full obstructions exist between the two antennas. By determining the specific line of sight conditions in the Wi-Fi network area, it can determine the correct type of wireless system to install. The area around the visual LOS that radio waves spread out into after they leave the antenna.

5.4 Static Antenna

As in [matyjas15], the receiver adopts the number of LDWuRs in different directions for static antenna. In general, the receiver's polls LDWuR for each direction in turn to explore the transmitter's direction. Then, the average total power consumption can be calculated as shows in Figure 10:

$$P_t^{sta} = \frac{\sum_{i=1}^{N_{dir}} P_t T_{scan}}{N_{dir} T_{scan}} = P_t$$

Figure 10 : The average total power consumption [matyjas15]

For instance, the receivers used four LDWuRs in different directions, such as east, west and north. Figure 10 shows one of four LDWuRs scan the north direction with 90 degrees.

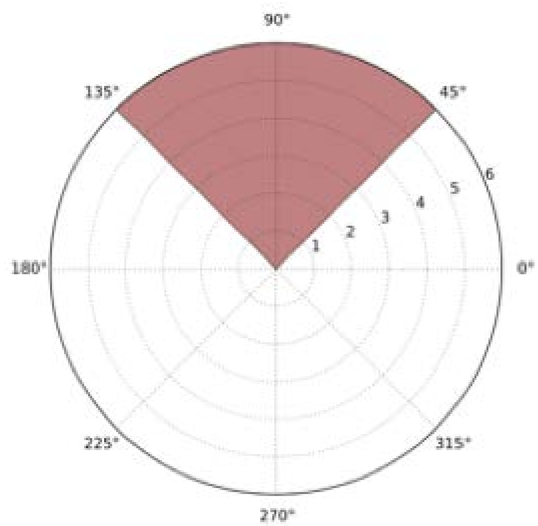


Figure 11 : One of four LDWuRs scan the north direction with 90 degrees [matyjas15]

5.5 Dynamic Antenna

A dynamic antenna uses a technique which the receiver adopts multiple LDWuRs [matyjas15]. In this method, each LDWuR consists of a WuR built in an omnidirectional antenna. Multiple LDWuR control a beam in different direction in turn. As a result, the receiver can use a beam to detect a transmitter's direction. The receivers adopt three LDWuRs to cooperate to form a beam in different directions with a certain degree of cover range. The LDWuR with omnidirectional antenna of 1/omnidirectional antenna times power consumption to explore transmitter's direction.

6.0 Summary

In this paper we have discussed the related works of LRLP wireless network such as power management mode, modulation and addressing, channel coding and beamforming. Although many efforts to design and implement LRLP is still on-going, the actual implementations have not been studied or reviewed rigorously. Many research is still ongoing as the future standards and technologies are emerging rapidly.

We also surveyed several works done by previous researchers to make LRLP possible. The experiments conducted by the researchers confirm that the implementation of LRLP can be realized with the technologies and method that have been tested. Even, some technologies of IoT communication have achieve that such as Sigfox and LoRaWAN. Beside that, some required action is needed for future research of IEEE 802.11ah deployments since it will be deployed in the near future in various regions, including China, Europe, Japan, Singapore, South Korea, and USA. Overall, numerous common features such as many bands, flexible bandwidth, FDD/TDD, MIMO/Beamforming, H-ARQ and OFDMA have great attention among researchers to discuss and explore.

List of Acronyms

AES	Advanced Encryption System
AP	Access Point
ASK	Amplitude Shift Keying
BSS	Basic Service Set
DS	Distribution System
DSSS	Direct Sequence Spread Spectrum
ESS	Extended Service Set
ETSI	European Telecommunications Standards Institute
FHSSS	Frequency Hoping Sequence Spread Spectrum
GHz	Gigahertz
GFSK	Gaussian Frequency SK
BPSK/QPSK	Binary/Quadrature phase SK
IEEE	Internet Engineering Task Force
IPv6	Internet Protocol Version 6
IoT	Internet of Things
ISM	Industrial, Scientific and Medical
kbps	Kilobit per second
LDWuR	Long Distance Wake Up Radio
LTE	Long Term Evolution
LOS	Line of Sight
LoRaWAN	Long Range Wide Area Network

LRLP	Long Range Low Power
NLOS	Non Line of Sight
mA	milliamps
MB	Multiband
MAC	Media Access Control
MIMO	Multiple Input Multiple Output
MQTT	Message Queue Telemetry Transport
OFDM	Orthogonal Frequency Division Multiplexing
OOC	Optical orthogonal code
OOOK	Orthogonal on-off keying
LTN	Low Throughput Network
PHY	Physical
PDet	Probabilities of Detection
PN	Pseudo Noise
RF4CE	Radio Frequency for Consumer Electronics
SSID	Set ID
TIM IE	Traffic Indication Map Information Element
HomePlug-AV	HomePlug Audio-Visual
IE	Indication Element
STAs	Wireless Stations
TSCH	Time Sloted Channel Hopping
Tx BF	Transmit Beamforming
TDMA	Time Division Multiple Access
V	Volt
WEP	Wired Equivalent Privacy
WuR	Wake Up Radio
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access

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