RONJA and Free Space Optics

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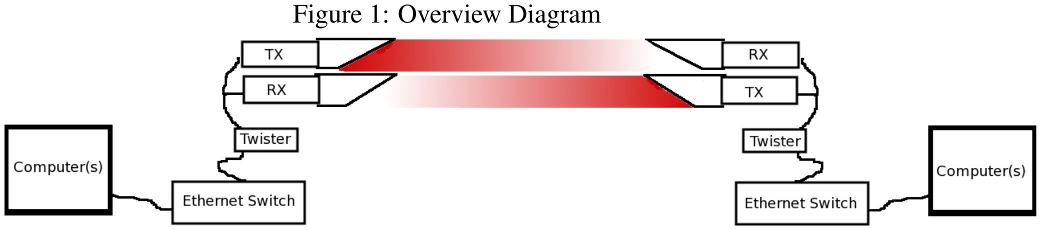
1 Overview

RONJA (Reasonable Optical Near Joint Access) Tetrapolis – Allows one to make a free space 10Mbps full-duplex[1] Ethernet bridge between two points up to 1.4 km away using visible incoherent light. Plans to build the necessary components to make a Ethernet bridge are located on the RONJA website[1]. This paper will cover how the RONJA works as well as explain certain design observations.

As shown in Figure 1, the RONJA Tetrapolis consists of a Receiver (RX) and Transmitter (TX) at both sides of the bridge. The transmitter sends a signal with a Light Emitting Diode (LED), the light rays are collimated (paralleled) by a lens. On the other side of the bridge the receiver uses another lens to focus light onto a photo diode. The Twister is the electronics that cleans up the signal, adds a 1Mhz pulse when no data is being communicated, and adds the link integrity pulse back to the Ethernet cable. The 1Mhz pulse is used to keep the RX knowing what a signal is over noise.

Figure 1: Overview Diagram



1.1 Uses

Possible uses would be to expand a network between buildings without having to dig in the ground and lay cable. Such examples are: a network connection between a home and workshop, between an individual's home and their friend/families house, to connect two company buildings, to connect university buildings, a temporary point to point network after a disaster, etc.

[1] Communication in both directions simultaneously, auto-negotiation not supported.

They can be used to provide Internet/TV/phone access. It could be a replacement for last mile service (A replacement for telephone cable, coax cable, satellite), using multiple RONJA they could be used in a mesh (See Figure 2) or star (See Figure 3) network topology to connect homes/businesses to the Internet in urban, rural, or undeveloped areas. The RONJA can be used as a cheap way to start up a local telecom or Internet Service Provider.

It can also be part of a redundant network bridge where you use radio wave communication as well as the RONJA and one of them takes over if the other fails. This should provide you with increase network reliability.

There is no licensing of spectrum that needs to be done with the FCC since it just uses plain light, it is also incoherent so the FDA does not need to be involved[5]. You wont have interference from other radio frequencies.

The RONJA works fine in rain/snow/daylight, it does however have problems in heavy fog. It does need to be placed in a area where the sun is not directly behind a transmitter. It is designed to be reliable up to 1.4km in 4km or better visibility.

Figure 2: Example of a small mesh network - if F wanted to communicate with A the data could go F,E,D,C,B,A or F,G,B,A. Each line represents a RONJA set. F to E is a RONJA set as well as F to G. F has two RONJA's installed one pointed to E and one pointed to G.

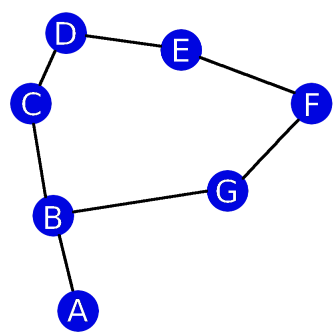
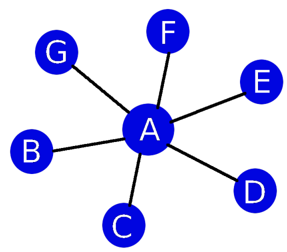


Figure 3: Example of a small star network - if E wanted to communicate with B it would go E,A,B. In this diagram A would have 6 RONJA install each one pointed to one of the others around it.



2 Free Space vs. Radio

Radio (Such as IEEE 802.11) can also be used to create a network bridge. Free Space Optics have some advantages and disadvantages compared to Radio.

2.1 Eavesdropping

Because of the nature of radio waves, it is harder to contain where the radio waves go, even in directional point to point networks a signal can still be eavesdropped over a large area. For example a typical parabolic antenna has a beam width of 16°, at 1.4km one would still be able to receive the signal 194 meters on either side of where it is pointing. The signal can also be listened to behind the intended location. With a free space network you must intercept the light beam, this is much more difficult and can be detected.

2.2 Interference

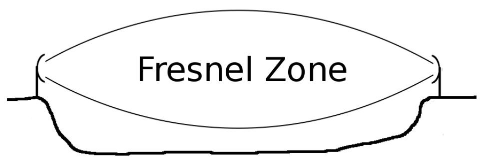
Radio waves can interfere with each other. This interference is one of the reasons the FCC licenses spectrum. There are blocks of spectrum free to use, but other devices are also using them. As an example if you used the public block in the 2.4GHz range, your signal can get interference from portable phones, wireless access points, microwave ovens, car alarms, and security cameras. This can make your signal less dependable.

Free space optic networks are free from these types of interference.

2.2.1 Fresnel Zones

The Fresnel zone of light is very small compared to radio waves. If there is an obstruction in the first Fresnel zone it will produce interference. From [6] the largest radius in the Fresnel zone is $R_1 = \sqrt{\frac{1}{4}\lambda D}$, where D is the distance between the TX and RX. For $D = 1.4km$ and $\lambda = 630nm$ $R_1 = 15mm$, with $\lambda = 12cm$ (As in a 2.4Ghz signal) $R_1 = 6.5m$. The first Fresnel zone for our radio wave signal is about as tall as a two story house, even if mounted on the roof of a two story house, the earth could be in the first Fresnel zone.

Figure 4: Fresnel Zone - Notice it is not just a straight line from one end to the other, it widens the farther you go from both ends.



2.3 Distance

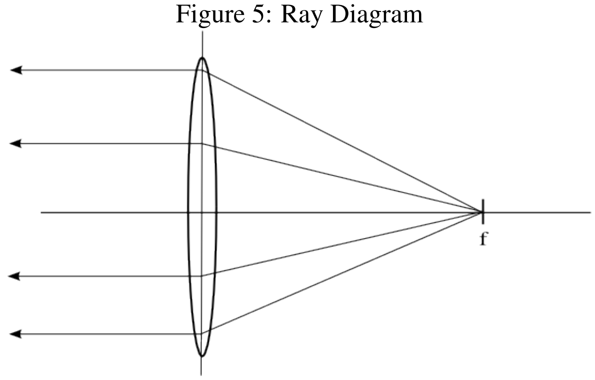
Radio waves have improved distance over free space optics. Free space optics is limited to how far it can travel through the atmosphere because of absorption.

3 Optics

3.1 Geometric

The RONJA uses a double convex spherical lens, which is typical found in magnifying glasses. As shown in Figure 5, the RONJA uses the lens to take light from a LED and collimate it, as well as take incoming light into a point. For our implementation of the RONJA we used lenses with a 301mm focal point and 127mm diameter (f/2.4).

Figure 5: Ray Diagram



4 Electronics

4.1 Light Emitting Diode (LED)

An LED is a semiconductor diode that emits incoherent narrow-spectrum light when an electric current is applied. Entire papers can be written on LEDs alone. For a brief explanation on how LEDs work see [3].

The RONJA makes use of the HPWT-BD00-F4000 LED by LUMILEDS. This LED has a peak wavelength of 640nm with FWHM of 28nm. A response time of 20ns (50MHz) and Luminous flux from 3 to 7.3 lm[2].

4.2 Photodiode

A photo diode is a photo detector that can converts light into a change in current or voltage. Like the LED more information can be found in [3]. The photo diode is used to receive the signal emitted by the LED from the transmitter located at the the other side of the bridge.

The RONJA uses the VISHAY BPW43 photo diode which has a response time of 8ns (125MHz), and range of spectral bandwidth 550-1000nm with peak sensitivity at 900nm. The relative spectral sensitivity at the peak wavelength of the LED used is approx 0.65 [4].

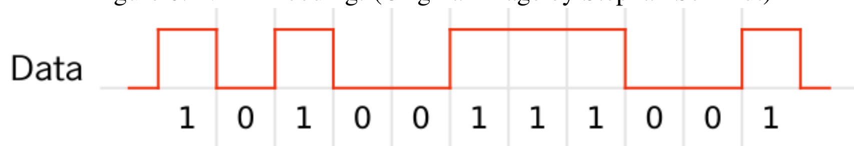
5 Signals

Information in a computer is stored as a set of hi/lo values or binary. For example, an ASCII 'a' is represented as 01100001. This can be communicated as two sets of different voltages, or like in the RONJA blink on and blink off. There are many ways to encode the information to make it more resistant to noise or to make sure that timings are synchronized. The next subsections go over some of the encodings used in Ethernet 10BASE-T and 100BASE-TX. The RONJA currently supports 10BASE-T.

5.1 NRZ Encoding

NRZ (Non-Return to Zero) is a simple encoding, hi for 1 and lo for 0, each bit delimited by time (See Figure 6). In NRZ, clock timing is important and is often used internally when everything is operating off the same clock. Imagine a long stream of 1's there would not be any indication of how to set your clock between bits. If this information is sent to another system that has a slightly different clock, it could easily become out of sync.

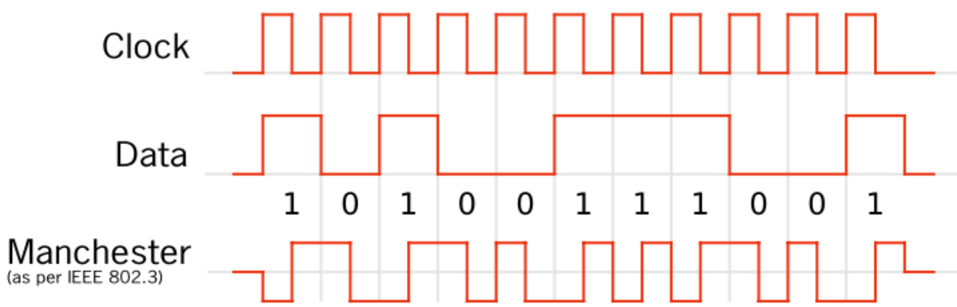
Figure 6: NRZ Encoding. (Original image by Stephan Schmidt)



5.2 Manchester Encoding

An Ethernet 10Base-T network sends it's data in a Manchester encoding [7]. A property of the Manchester encoding is that it needs twice the bandwidth of the data compared to NRZ, thus a response capable of 10Mhz is needed (1 Hz/bit). Our LED and photo diode are capable of handling these response times.

Figure 7: Manchester encoding, an XOR like scheme. (Original image by Stephan Schmidt)



5.3 4B5B

4B5B is an encoding that transmits 4 bits of information using 5 bits of data. It makes sure that there is always a shift between 1 and 0 in 4 bits of data, to make synchronizing of time easier. In normal NRZ if the data is a long series of 1's it would not transition from high to lo until it reached a zero. With 4B5B there is a guarantee transition so the receiver clock can be resynchronized with the transmitter. 4B5B lets you synchronize the clocks while using NRZ. 4B5B is used in 100BASE-TX networks. This increases the required bit rate through the cable to 125Mbit/s.

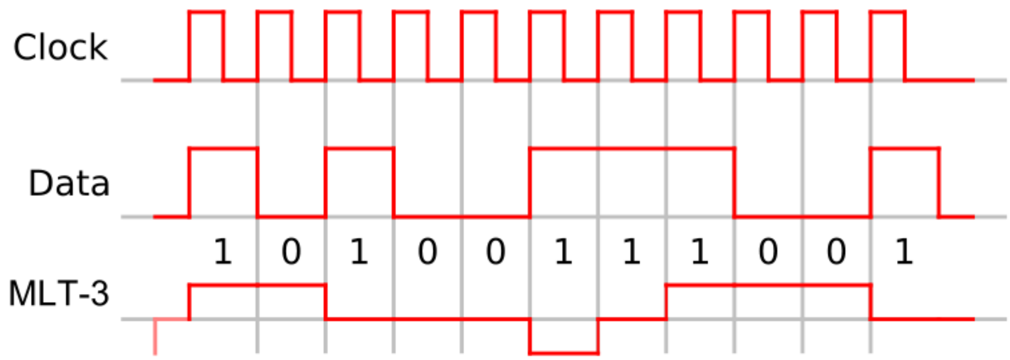
Table 1: 4B4B Data Encoding

Name	4B	5B
0	0000	11110
1	0001	01001
2	0010	10100
3	0011	10101
4	0100	01010
5	0101	01011
6	0110	01110
7	0111	01111
8	1000	10010
9	1001	10011
A	1010	10110
B	1011	10111
C	1100	11010
D	1101	11011
E	1110	11100
F	1111	11101

5.4 MLT-3

MLT-3 is a encoding used in Ethernet 100BASE-TX. It changes from it's current state to the next every time there is a high. It has 3 states: typically positive, zero, and negative. A reason to use this encoding is to reduce the frequency by four (one cycle: hi-med-lo-med) compared to something like Manchester. This makes it easy to be transferred in copper cable. It reduces the frequency traveling through copper cable for the 100BASE-TX to 31.25 MHz. This is of no help in reducing the frequency when you have only two states on and off. Creating a third state with the LED alone (such as half intensity), would reduce the range.

Figure 8: MLT-3 Encoding. (Image by Invitatious)



6 LED vs LASER

A common response to those introduced to the RONJA is that a LASER should be used instead of a LED. This section will try to compare a LASER vs LED.

6.1 Response Time

The LASER has an advantage of shorter response times than the LED. The LASER diode is stimulated to emit instead of spontaneous like the LED. LASER diodes with less than 1ns (1Ghz) response times are available. It is hard to find diodes with less than 20ns (50Mhz) response times. The LED response time works fine for the RONJA(10Mhz), if we wanted to make a faster link, this is where the LASER could have an advantage (See Section 7.4).

6.2 Monochromatic

A LASER tends to emit a beam more monochromatic (<5nm FWHM, compared to > 24nm FWHM), it makes it easier to add filters to the optics to only allow the light from the LASER wavelength reducing ambient noise, and possibility of photo diode saturation from outside sources.

There are also disadvantages, because of the narrow wavelengths emitted by the laser there could be conditions where that wavelength is absorbed, such as certain ice crystals in the air that absorb certain narrow bands of wavelength. With the LED you are emitting a much broader set of wavelengths. If some of it gets absorbed, you still have the rest to fall back on.

6.3 Scintillation

Scintillation can be far worse for a LASER than the LED because the LASER is more coherent than the LED. As the beam travels through the air, it will hit packets of air of different temperature which have a different index of refraction causing constructive and destructive interference which can ruin your signal. This effect can be especially bad depending on the terrain it travels over. Asphalt, ponds, fountains, all create temperature differences that will contribute to scintillation.

If you use a LED or LASER the effects of scintillation can be reduce by using large lens (aperture averaging). Even if a LASER is used and even though the LASER is already collimated, lenses to get a larger beam should be used to avoid local coherence. As explained in [9] the minimum lens diameter to avoid local coherence should be larger than the central diffraction zone and is given by:

$$D_R > \frac{L\lambda}{D_T}$$

With D_R the diameter of the receiver lens, D_T the diameters of the transmitter, L the length of the link, and λ the wavelength of light used.

For a audio comparison of the difference in scintillation between a LASER and a LED for a long distance optical link, see [8].

6.4 Safety

LASERs can be dangerous. Devices sold to the market place that contain lasers must go through the FDA. Even low powered lasers should have extra safety precautions such as auto shutoff if there is a beam break. For lasers rated higher than IIIa/3R protective eye goggles are needed when working with them. Even light reflected after it has hit a object can be enough to damage the eye depending on the power and wavelength of the LASER.

The LED emits a more wider spectrum and is much safer.

7 Further Topics and Improving the Ronja

7.1 Mount Considerations

The distances involved requires that the mounts be very stable. If the wind causes an angle change, the end point will be displaced $s = d\tan\theta$, where d is the distance between points and θ is the angle change caused by the vibration. An end point displacement of 20cm when $d = 1.4$km is only an angle change of $\theta = 0.008°$. If mounted on tall buildings, the swaying of the building can also be a problem as the current design does not compensate for that.

At large distances, aiming is difficult. The original RONJA design has a mechanism to make fine adjustments. Improvements to the RONJA design might be a finder scope and auto aiming mounts.

7.2 Fresnel Lenses

Fresnel lenses give you large apertures and shorter focal lengths, while still being light weight. It may be possible to use a large Fresnel lens to get a better signal from the transmitter, or to make the optical tube shorter (smaller focal length). When shortening the focal length extra ambient light may get to the photo diode and that would need to be considered in the design.

7.3 Shorter and Longer Distances

There may be instances were one needs to create a shorter or longer network bridge. The use of smaller lenses at short distance maybe also be beneficial at times. If a link of smaller than 90m is needed a few of the electronics (a capacitor and resistor) need to be changed in the receiver (See [12]). To get a longer signal you can also use two or more transmitters pointed to one receiver. A discussion of using multiple transmitters can be found at [10] and [11].

7.4 Faster Data Transfer

As noted in Section 4.1, our LED has a max response of 20ns (50Mhz). So we would run into a problem if we wanted to increase the speed to 100Mbits/s by transmitting in a similar manner with the LED.

There are a few solutions. We could use a LASER which has much faster response rates than LEDs and read in the MLT-3 and transmit NRZ at max frequency of 62.5 Mhz, with the receiver converting NRZ back to MLT-3. We can also communicate in parallel instead of serial, we would require several transmitters and receivers. For example if we had three transmitters/receivers then each transmitter could handle a maximum frequency of 21Mhz. Using multiple transmitters/recievers brings up several issues: noise from other transmitters, 4B5B would not guarentee a hi-lo transition for each detector, mounting space issues. One thing is certain making a 100Mbit/s network would be much more complex.

8 Conclusion

The RONJA is a viable alternative to other ways of creating a network bridge. With 150 links deployed [1] and the design plans free to use, the author wonders why we haven't seen more of these.

References

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