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A low cost short reach analog fiber optic link for EMBRACE

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Abstract

This is a technical note to study the possibility of using a low cost analog fiber optic link for EMBRACE, a SKA project proposed by ASTRON, Netherlands. The note is a design guide to an analog fiber optic link and describes the optimization of component specification to meet the performance and low cost requirement for the short distance link. A cost comparison is done with a coaxial cable link approach to the project. The design brings out the input and output specification for the link which will be useful while designing the front-end and back-end system for the project. The current trends in building a low cost and short reach analog fiber optic links are covered with details of reference in the later section of the report.

1.0 Introduction

The antenna array consists of 625 tiles and each tile is made up of 64 antenna elements. Each tile gives two RF outputs covering 450 MHz to 1550 MHz. The instantaneous bandwidth of the RF output is 40 MHz over the above band. The RF output brings in the analog beam formed within the tile. Two analog fiber optic links are needed to connect the two RF outputs to the nearest signal processing station, which is 100 meters away. A total of 2x625 analog beams need to be connected to the station and require 1250 analog fiber optic links. Since the number of links being high and the distance being short a cost-effective solution is being studied here. The application is similar to cellular application where RF over fiber link is used for their distributed antenna system (DAS) under a roof.

2.0 Coaxial cable approach

Coaxial cable link is a ready solution for the antenna array. Table 1 describes the best-known RF cable specification and its cost for the project. LMR1700 coaxial cable has low loss and better frequency response, but costs more than a fiber optic link. RG214 is cost effective but has very high attenuation and poor frequency response and could not meet the project specification. The link with RG214 requires a high gain amplifier and an equalizer. Cost analysis for the cable approach is done without including the cost of RF connectors and RF amplifiers needed to support the cable loss. A need for a low-cost analog fiber optic links is clear from the performance and cost analysis shown in table 1.

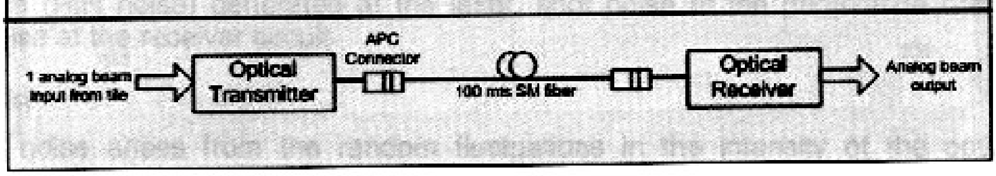
Table 1. Coaxial cable link for EMBRACE [1]

Cable Type	Attenuation in dB/100 ft @ various frequency				Cost in $		
	400 MHz	900 MHZ	1500 MHz	2000 MHz	Cost / 100 ft	Cost / link (100 meters)	Total cost 1250 link
LMR1700	0.632	0.936	1.26	1.50	717,00	2352,33	2940417,00
RG214	100 MHz	400MHz	1 GHz	3 GHz			
	2.60	6.8	12.0	25.0	165,00	541.332	676665,00

3.0 Analog fiber optic link

RF over fiber uses an analog fiber optic link to transmit from one station to another. A point-to-point link consists of a laser which is directly (intensity) modulated by the RF signal at the transmit end and received by a photodiode employing direct detection at the other end. The link is normally referred as intensity modulated direct detection (IMDD). Figure 1 shows the basic configuration proposed for EMBRACE.

Figure 1. A COST- EFFECTIVE SHORT DISTANCE ANALOG FIBER OPTIC LINK



The RF input power applied to the laser input impedance causes a modulation of the laser bias current (I_{bias}), which in turn modulates the intensity of the light source. The intensity-modulated light is sent through a fiber to a photodiode at the remote end for detection. A photocurrent is produced at the photodiode, which produces the RF signal across the load impedance R_{load}. The link being short distance an external modulation is not cost-effective. Normally an application whose modulation frequency is very high above 8 to 10 GHz an external modulation is preferred. Table 2. Show the input specification for the proposed analog fiber optic link.

Table 2. Link input specification

Parameter	Value
1. Laser relative intensity noise (RIN)	-157 dB/Hz
2. ($I_{bias} - I_{threshold}$)	20 mA
3. Laser slope efficiency (η_l)	0.05 W/A
4. Max. Optical power (P_{max})	2 mW
5. Photodiode responsivity (R)	0.85 A/W
6. RF amplifier noise figure (NF)	2 dB
8. RF amplifier gain (Gamp)	30 dB
9. Optical return loss of photodiode	>40 dB
10.Optical return loss of connector	>60 dB
11. P1dB compression point of laser	> 10 dBm
12. IIP3 (3rd order intercept point)	> 20 dBm
13. RF input and output impedance	50 Ω

4.0 Link design[2]

4.1 Intrinsic gain

The analog fiber optic link has a conversion loss given by equation1. Due to the parallel combination of R_{load} and the output impedance only half of the detected photodiode current is available and hence the factor ½ is used in equation 1,2 and 4. The link has a conversion loss of –33.45 dB and with an optical loss of 1 dB in the link the total RF loss will be 35.45 dB. The conversion loss is also referred as intrinsic gain of a link. With better slope efficiency and reactive impedance matching at the laser and photodiode the loss can be reduced. VCSEL laser has higher slope efficiency compared to FP and DFB lasers and help in improving the conversion loss of the link. The intrinsic gain increases with an increase in optical power of an externally modulated link. A directly modulated link does not shown any improvement in gain with increase in optical power.

$$G_i = 10.\text{Log}10(\ \eta_l \, . \, R / 2\ )^2 \qquad \text{--- (1)}$$

Where η_l = Slope efficiency of the laser diode in W/A
R = Responsivity of the photodiode in A / W

4.2 Noise performance of the link

The total noise performance of an analog fiber optic link depends on the individual noise contribution of various components in the link. Three major noise sources in an analog link are Laser noise (RIN noise) generated at the laser, shot noise at the photodiode detection and thermal noise at the receiver circuit.

a. Laser noise

The laser noise arises from the random fluctuations in the intensity of the optical signal generated at the laser diode. The laser noise is measured directly at the transmitter and is referred to as relative intensity noise (RIN) in the laser diode specification. The RIN is the ratio of mean square amplitude of the noise fluctuations per unit bandwidth ($<P^2>$) to the square of the DC optical power (Po^2). The laser noise power P_{laser} in an analog fiber optic link for direct detection is given by equation 2.

$$P_{laser} = RIN_{laser}.(I_{ph} /2)^2.R_l \quad \text{--- (2)}$$

Where

Photodiode current $I_{ph} = (I_{bias}-I_{th}).\eta_l.R.\alpha$ --- (3)

η_l = Slope efficiency of the laser in W/A
α = Optical loss in ratio [$10^{(-\text{optical loss in dB} / 10)}$]
R = Responsivity of the photodiode A/W
R_l = Load resistance at the photodiode receiver
($I_{bias}-I_{th}$) = Bias current above threshold current mA

b. Shot noise

The average photocurrent generated at the photodiode is associated with a shot noise current generated due to the random process by which the current is generated at the photo detector. The shot noise power P_{shot} is given by equation 4.

$$P_{shot} = 2.e.[(I_{ph} + I_d)/2].R_l \quad \text{--- (4)}$$

Where e = Charge of the current carrier (1.6×10^{-19} C)
I_d = dark current of the photodiode in A

c. Thermal noise

Thermal noise is associated with the receiver circuit and the thermal noise power $P_{Thermal\_noise}$ is given by equation 5.

$$P_{Thermal\_noise} = k . T_o \quad \text{--- (5)}$$

Where k = Boltzman constant (1.38×10^{-23} J / K)
T_o = Temperature in Kelvin (290 K)

d. Total noise

The total noise is the summation of the above three major noise sources in a fiber optic link. The total noise power of the link $P_{total\ noise}$ is given by equation 6.

$$P_{total\ noise} = P_{nLaser} + P_{shot} + P_{Thermal\_noise} \quad \text{--- (6)}$$

4.3 Equivalent input noise (EIN in dBm/Hz) of the link

The EIN_{link} is the total noise referred to the link input by the following equation 7.

$$EIN_{link} = P_{totalnoise} / G_{link} \quad \text{--- (7)}$$

Where the link gain $G_{link} = (\eta_l.\alpha.R / 2)^2$

4.4 Noise figure of the link

The noise figure (**NF** in dB) of the link is given by the equation 8.

$$NF_{link} = (EIN_{link}\ dBm/Hz) + (174\ dBm/Hz) \quad \text{---} (8)$$

4.5 Noise equivalent bandwidth EIN_{bw}

The equivalent input noise for a given noise bandwidth is given by equation 9

$$EIN_{bw} = EIN_{link} + 10.\log_{10}(BW) \quad \text{---}(9)$$

4.6 Noise figure with a pre-amplifier

A pre-amplifier at the input of the fiber optic link will reduce the total noise figure of the link in addition to the gain. But a trade-off exists with the dynamic range of the total link. The link noise figure is much more dependent on the pre-amplifier noise figure and gain. Hence choosing a low noise amplifier is of importance. Equation 10 gives the link noise figure with a pre-amplifier.

$$NF_{total} = NF_{pre\text{-}amp} + (NF_{link} - 1) / G_{amp} \quad \text{---}(10)$$

4.7 Noise figure with a post-amplifier

A post amplifier connected at the output of the link will compensate the link loss but with an increase in noise figure. The total link noise figure for configuration of this type is given by equation 11.

$$NF_{total} = NF_{link} + (NF_{post\text{-}amp} - 1) / G_{link} \quad \text{---}(11)$$

5.0 Link performance

Table 3 shows the obtained link performance for the input specification given in table 2. The link design performance for various optical losses is shown in figure 2,3,4,5 and 6.

Table 3. Link performance without amplification

Link Parameter	**Value**
1. Link gain	-33.45 dB
2. Equivalent input noise of the link EIN_{link}	-135.54 dBm/Hz

3. Noise figure of the link NF_{link}	38.45 dB
4. 1 dB compression dynamic range (40 MHz instantaneous bandwidth)	$= P_{1dB} - EIN_{dBm/Hz} - 10\log10(bw)$ $= +10 - (-135.54) - 76$ $= 69.5$ dB
5. SFDR (40 MHz bandwidth)	$= 2/3(IIP3_{dBm} - EIN_{dBm/Hz} - 10\log10(bw)$ $= 2/3(20 - (-135.54) - 76$ $= 53$ dB
6. Minimum detectable RF input power for noise bandwdith (40 MHz)	-59.52 dBm
7. Minimum detectable RF input power for noise bandwidth (450MHz-1550MHz)	-45.12dBm
8. RF loss for 1 dB optical link loss	2 dB

Figure 2 show the gain for various optical loss of the link. For EMBRACE the optical loss is less than 1 dB and the gain will be about –35 dB. An RF amplifier is required to compensate the loss in the link. Figure 3 show the system is shot noise limited for the input specification taken for analysis. Since the RIN of the laser is kept low the system is not laser noise limited. An increase in RIN will lead to a laser noise limited system.

Figure 2. Gain Vs optical loss for the analog fiber optic link

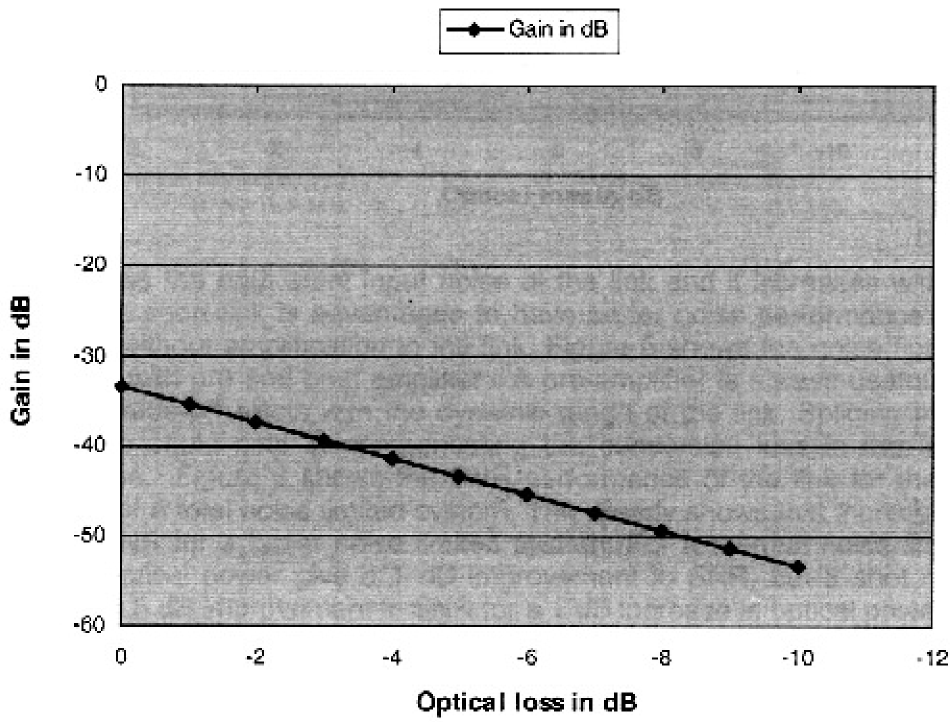


Figure 3. Noise performance of the analog fiber optic link

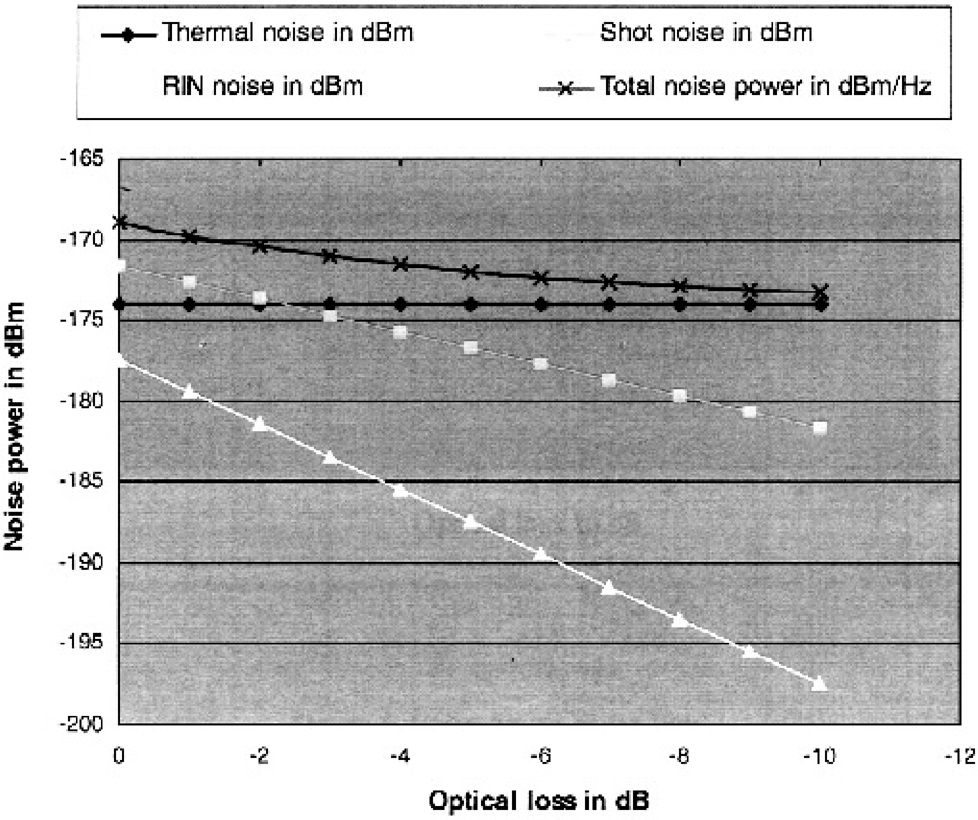


Figure 4 shows the equivalent input noise of the link and it increases with increase in optical loss. Hence a short link is advantages to have better noise performance. The noise figure is about 38 dB without amplification in the link. Figure 5 shows the noise figure for a link without amplifier and with pre and post amplifier. A pre-amplifier is always useful to reduce the noise figure but a trade-off exists with the dynamic range of the link. Splitting the gain between the two amplifiers could help in compensating the conversion loss in the link and have better dynamic range. Figure 6 shows the SNR performance of the link for the three noise limited system and for a total noise limited system. This clearly shows that increasing optical power do not help in SNR for a Laser noise limited system. For a thermal noise limited system a 1 dB increase in optical power give a 1 dB improvement in SNR, but a shot noise limited system show only a 0.5 dB improvement in SNR for a 1 dB increase in optical power.

6.0 Cost analysis

Table 4 shows the various components of the link and its approximate cost. *A cross check with the manufacturer is better for exact values.* The total cost can be brought down by $ 300 by building the laser driver and TEC circuit in house. Using a VCSEL laser whenever they are introduced in the market can bring down another $200. A cooled VCSEL laser at 1300 is more suitable but could cost more. It is mentioned in various literatures that VCSEL do not require cooling but needs to be studied if used for EMBRACE. The cost of the DC power supply is not included since it will be a common source for the whole array.

Figure 4. Equivalent input noise of the analog fiber optic link in dBm/Hz

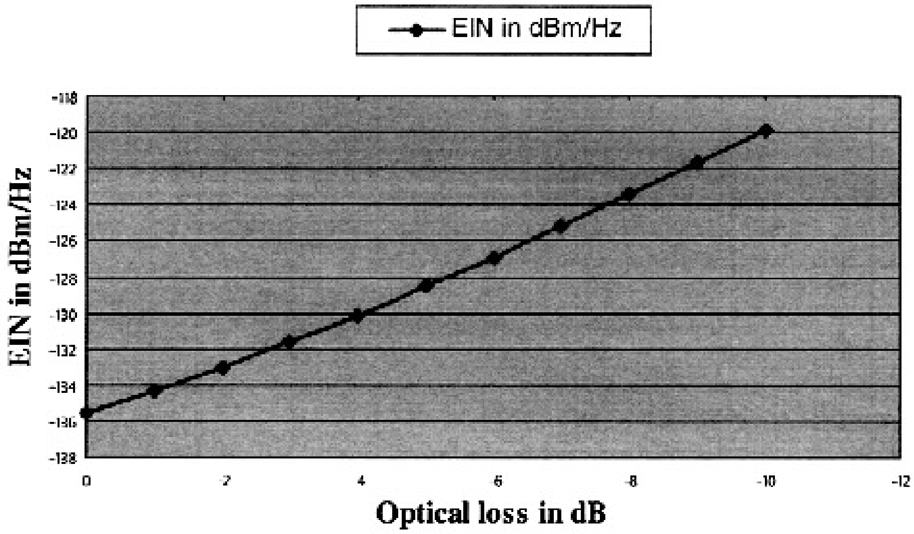


Figure 5. Noise figure of the link

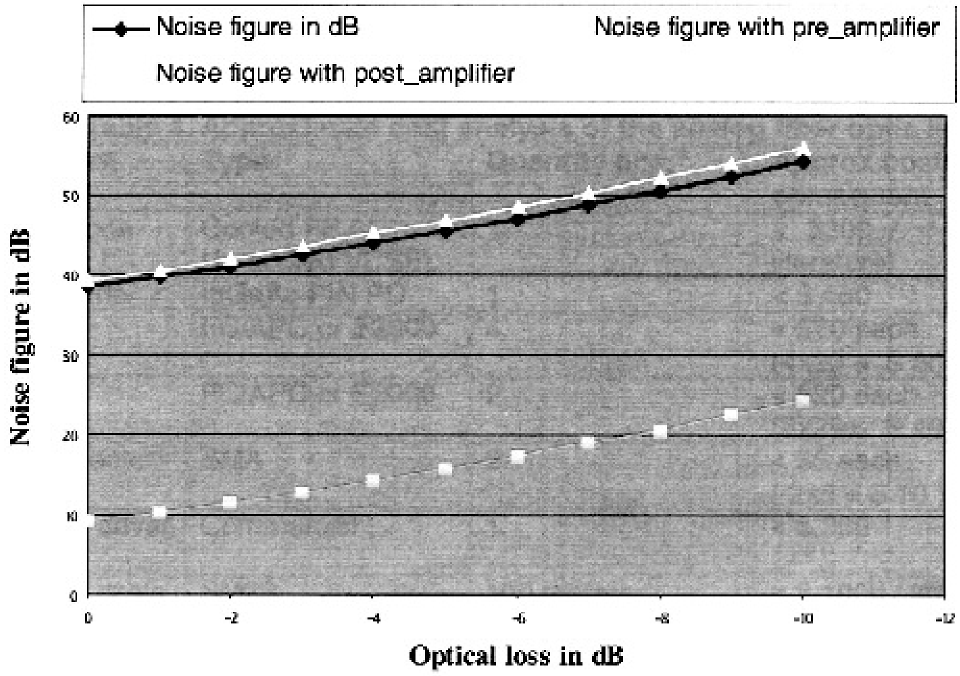


Figure 6. SNR performance of the analog fiber optic link

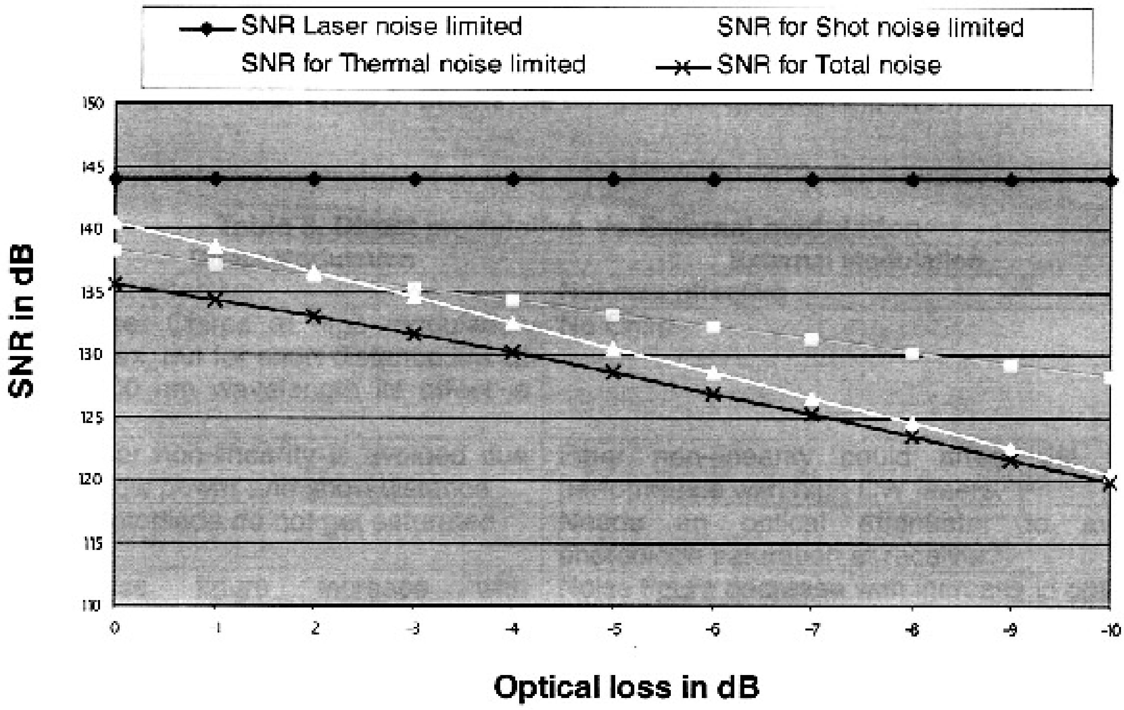


Table 4. Approximate cost analysis of the analog fiber optic link

Component	Type	Quantity nos.	Approx.cost/ component
1.Laser diode	Cooled FP / Un-cooled VCSEL	1	< $300 / < $ 80 (from literature)
2.Photodiode	InGaAs PIN PD	1	< $ 160
3.Optical connector	FC/APC or E2000	4	< $20 each (4x20 = $ 80)
4.Optical adaptor	FC/APC or E2000	2	< $20 each (2x20= $ 40)
5.RF connector	SMA	2	< $5 each (2x5 = $ 10)
6.Laser driver and TEC	Commercial	1	< $ 300
7.SM fiber cable	SM28	100 meters	< $ 1000 / km ($10 /100 meters)
8.RF amplifier	---	1	< $ 150
9.DC regulated power supply	Slow start, dual voltage	2 nos to supply full array at both ends	------
10.Total cost	Approximate	1 link	< $ 1050 (FP laser)

7.0 Requirement based analysis

7.1 Modulation

A direct modulated link is cost effective for short reach link and external modulation is a costly solution for EMBRACE. Table 5. Shows the comparison between the two modulations.

Table 5. Direct modulation Vs External modulation

S.No	Direct Modulation	External Modulation
1.	Cost effective	Not cost effective
2.	Laser Chirps at high modulation index, but for short distance link at 1300 nm wavelength its effect is low.	No Chirp
3.	Fiber non-linearity is avoided due to low power and short distance	Fiber non-linearity could affect the link performance with high CW lasers.
4.	Photodiode do not get saturated	Needs an optical attenuator to avoid photodiode saturation at receiver.
5.	Noise figure increase with increase in optical power.	Noise figure decrease with increase in optical power.
6.	Gain do not improve with increase in optical power	Gain increases with increase in optical power
7.	The relaxation resonance peak of the laser limits bandwidth.	The relaxation resonance peak of the laser does not limit bandwidth since modulation is independent of the laser.

7.2 Source

A short distances link can use a FP laser to keep cost low and they performance equal to a DFB laser. A VCSEL is basically a FP laser and cost-effective but its availability may take some time. A VCSEL single mode laser give a better performance compared to a multimode laser. Table 5 give general specification of a VCSEL mentioned in literature for analog modulation. Higher slope efficiency promises better intrinsic gain. But these lasers are normally available as un-cooled version and the temperature effect on the laser performance is to be studied if considered for the link.

Table 6. VCSEL analog specification (850 nm)

1. Laser Relative Intensity Noise (RIN)	> -120 dB/Hz
2. Threshold current	1.2 mA
3. Operating current	5 mA
4. Slope efficiency	0.8 mW/mA
5.Differential impedance	100 Ω

7.3 Optical power

Increasing the laser power improves SNR of the RF signal for a thermal noise limited system. A shot distance link is normally a Laser noise limited system, and increasing laser power do not benefit in SNR but lead to saturation at photodiode. Having a 5mW and 10 mW lasers increases cost and lead to fiber non-linearity.

7.4 Fiber

Multimode fiber systems are being developed to make use of an existing multimode fiber network. The multimode fiber has high loss and high modal dispersion. The fiber is more sensitive to temperature fluctuation and worth to study its effect on the RF performance. Table 7. Gives the specification of a broadband multimode fiber. The fiber cost for a short distance link like EMBRACE is negligible. Due to manufacturing cost a multimode fiber costs more than a single mode fiber.

Table 7. Multimode fiber - Corning infinicor 300 specification

1. Core diameter	62.5 μm
2. Loss @ 850 nm	< 3 dB/km
3. Distance bandwidth product @ 850 nm	200 MHz.km @ 850 nm
4. Loss @ 1300 nm	< 0.7 dB/km
5. Distance bandwidth product @ 1300 nm	500 MHz.km @ 1300 nm

7.5 Photodiode

Using external modulation requires a high-end photodiode, which can support higher optical input power and not cost-effective for a short distance link. The cost for a directly modulated direct detection link is low and gives a linear performance for short distance link.

7.6 Transimpedance receiver

Trans-impedance receiver provides good matching to the photodiode but it benefits only a thermal noise limited system. For a short distance link the amplifier increases both noise and gain equally and giving nothing in return. The short distance link is mostly a Laser noise limited system.

7.7 Phase stability[3]

The link being short distance and no LO signal is transported phase stability is less of a problem for EMBRACE. The link phase stability will do better with the fiber cable buried at about 1-meter depth. The temperature control of the laser should be effective to keep the laser maintain the temperature. It is worth studying the effect of temperature on the laser with the built in cooler. Since the array is exposed to external environment, the effect of external temperature on the laser reliability and performance need to be studied in detail. The change in delay through the fiber with change in emission wavelength and thermal expansion of the fiber is negligible for a short distance link, but becomes prominent at higher modulation frequency.

7.8 Optical reflection[4]

Optical reflection will be major problem for short distance links. Using ultra low return loss connector like E2000 of Diamond can help. Ensuring a 40 dB optical return loss for the photodiode can help in keeping the reflection-induced noises further low. The splicing joints should be arc fusion splice to avoid reflective joints. The above care will prevent the need for an optical isolator and saves on cost of the link. Other back-scattering induced noises are not applicable for short distance links. The Fabry Perot laser needs an optical isolation of 30 dB to avoid any degradation in SNR and IMD performance. A DFB laser requires more than 45 dB to keep noise and distortion low. Thus keeping the over all link reflection below the required isolation could avoid an optical isolator at the laser. A DFB laser normally comes with a built in isolator.

7.9 DWDM system

A dense wavelength division multiplexed system is compact by combining many analog channels in few fibers. The link is expensive due to the use of DFB lasers and DWDM mux and de-mux units. In addition a DFB laser should have a very tight specification to its wavelength and its isolation to other channels. The optical transmitter being in open space the temperature could badly affect the wavelength stability of the laser and the signal of one channel could leak to the other very easily. Above all the configuration saves on number of fibers but the system cost is very high compared to the point-to-point link.

8.0 Current trends in short distance analog fiber optic links

A short reach analog fiber optic link to EMBRACE is an application similar to low-power wireless network inside office buildings, airports, shopping centers, railway tunnels etc. A distributed antenna system (DAS) uses the radio over fiber systems to distribute the high frequency analog signal from their base station to their antenna locations under a roof. The optical transceivers cost them $1500 to $3000 depending on their dynamic range[5]. These systems are designed to cover 100 to 300 meters and cover frequencies greater than 2 GHz.

The trend is to use RF over single mode fiber[6] and IF over multimode fiber[7]. RF over single mode fiber keeps cost low by using Fabry perot laser for short link length and links having less number of radio carriers. For longer span a DFB laser is used for better linearity and lower noise performance. A typical (amplified) optical link[5] at 1310 nm gives a gain of 0 dB, noise figure of 13 dB, input third order intercept point of 25 dBm and a spur-free dynamic range of 100 dB.Hz2/3. This performance is very similar to the link proposed in this report for EMBRACE with a pre-amplifier. When the RF signal is of very high frequency bringing it as IF could help in using the IF over multimode fiber system for low cost.

8.1 RF over multimode fiber

A multimode fiber limits the bandwidth to around 500 MHz.Km at 1310 nm due to modal dispersion. As explained earlier it is more attractive to use pre-installed multimode fibers since single mode dark fibers could cost high for these cellular operators. Transmission of high frequency radio carriers over multimode fiber has been demonstrated recently[7]. The system shows a dip in the response due to modal dispersion.

8.2 VCSEL

A VCSEL operating at 850nm used for Gigabit Ethernet (GBE) using multimode fiber cost about $30 each and they are available with SC or ST receptacles. Recently[8] these devices were tried for analog links over 300 m high bandwidth multimode fibers and could get a SFDR of 97 dB.Hz2/3 for frequencies up to 5 GHz. But all these application use un-cooled laser and the effect of temperature for radio astronomy application needs to be studied before using them.

Similarly low cost, edge-emitting lasers using advanced multi-quantum well lasers in TO can package developed for 2.5 Gbps digital application can be used with single mode fiber for analog application.

It has been seen that a single mode VCSELs have superior noise and distortion characteristics compared to multimode VCSELs, but has higher conversion loss due to their large impedance mismatch and low slope efficiency (0.2 W/A). Recent development [9] show a VCSEL with 80 Ω differential resistance and a slope efficiency of 0.8 A/W can obtain a link gain of –20 dB and a NF of 30 dB, while still having a High SFDR of 110 dB.Hz2/3 at 2 GHz and 105 dB.Hz2/3 at 5 GHz. Any application above 10 GHz requires an external modulation, but with a 10 VCSEL developed for 10 Gbps could cover an analog bandwidth 0.5-11 GHz and could cost $1,250 in future [10].

9.0 Conclusion

The proposed link shows the possibility of having a low cost short distance analog fiber optic link for EMBRACE bringing in the full RF band. With the availability of VCSEL laser the link could cost low compared to a link using FP laser diode. Recent work has shown that VCSEL used for Gigabit Ethernet can be used for analog optical links. It was shown that a 300-meter high bandwidth multimode fiber could transport frequencies up to 5 GHz with a SFDR of 97 dB.Hz2/3. The effect of temperature on the device performance is to be studied for an application like EMBRACE where the array is exposed to external environment. All current technology uses directly modulated semiconductor laser transmitters and PIN photodiode receivers for simplicity and low cost for short distance links. The link being short the advantage of cost could be obtained by optimizing the component specification with the actual requirement of the project.

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