Replacing MOOS fiber communication link with copper loops using xDSL

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MOOS communication, MOOS cable, copper communication, DSL, ASDL, SHDSL

ABSTRACT

The existing fiber optical communication link in the MOOS system has low power consumption and transmits information at a very high bit rate. But fiber optical components are expensive and delicate. Currently the MOOS system does not need such a high bit rate and could conserve power by bursting data a few times a day. By replacing the fiber communication link with a copper link using a long distance DSL modulation technique the MOOS system could maintain its current performance while significantly reducing its cost, a major issue with the system. If, in the future, a high bit rate sensor payload was desired, a MOOS system using the existing fiber link or a hybrid copper/fiber system, could be implemented. But for the current MOOS systems, significant money could be saved using a copper based DSL communication link.

INTRODUCTION

The required specifications for the communication link on the MOOS systems are:

- Distance requirement: 10 km
- Bit rate of at least 7200 bps
- Able to run next to 400VDC power cable
- Minimize power usage

The requirement to run next to the 400VDC power cable is not negotiable, the modems and cable design must overcome any noise from the power cable. The bit rate and power usage requirements are dependent on each other. For example, if a high bit rate was achieved, then higher power consumption could be tolerated. The distance requirement is the specification for a complete MOOS communication link distance, and for a purely copper MOOS system, is set. For a hybrid copper/fiber system, it could be reduced.

A comparison of communication schemes was previously done by Lance McBride comparing a number of copper and fiber communication protocols. As can be seen in Figure 1 the fiber protocols are the only ones which can function at distances up to 10 km. Figures 2 and 3 show the comparisons of bit rate and power consumption.

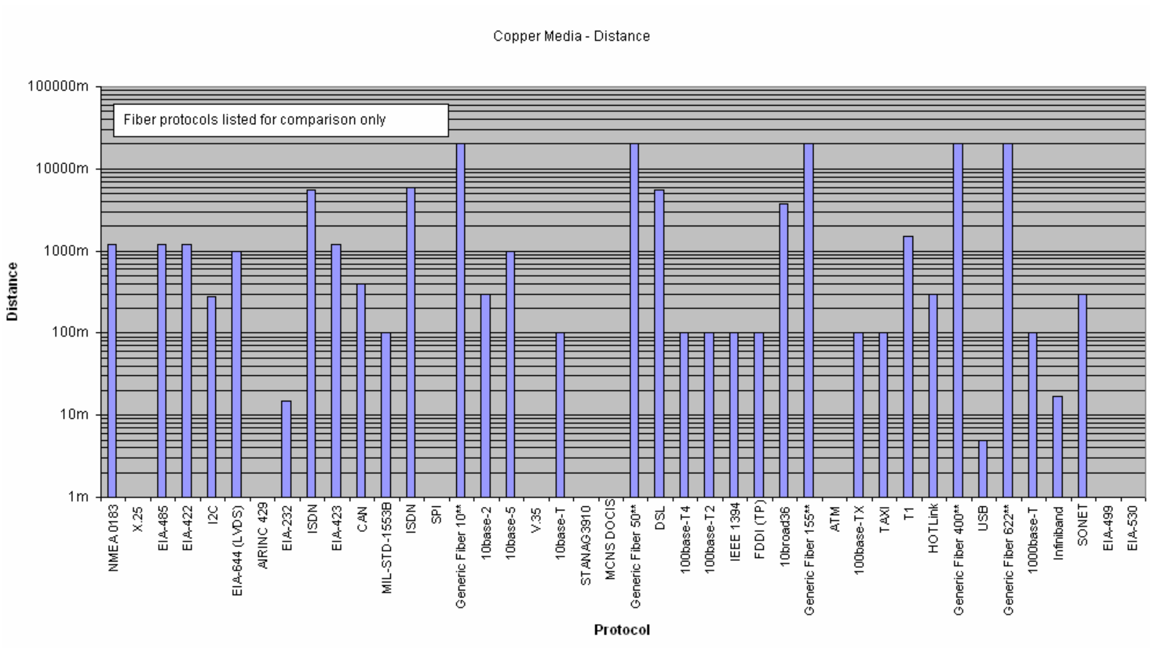


Figure 1: Chart comparing maximum distance achievable by different communication links.

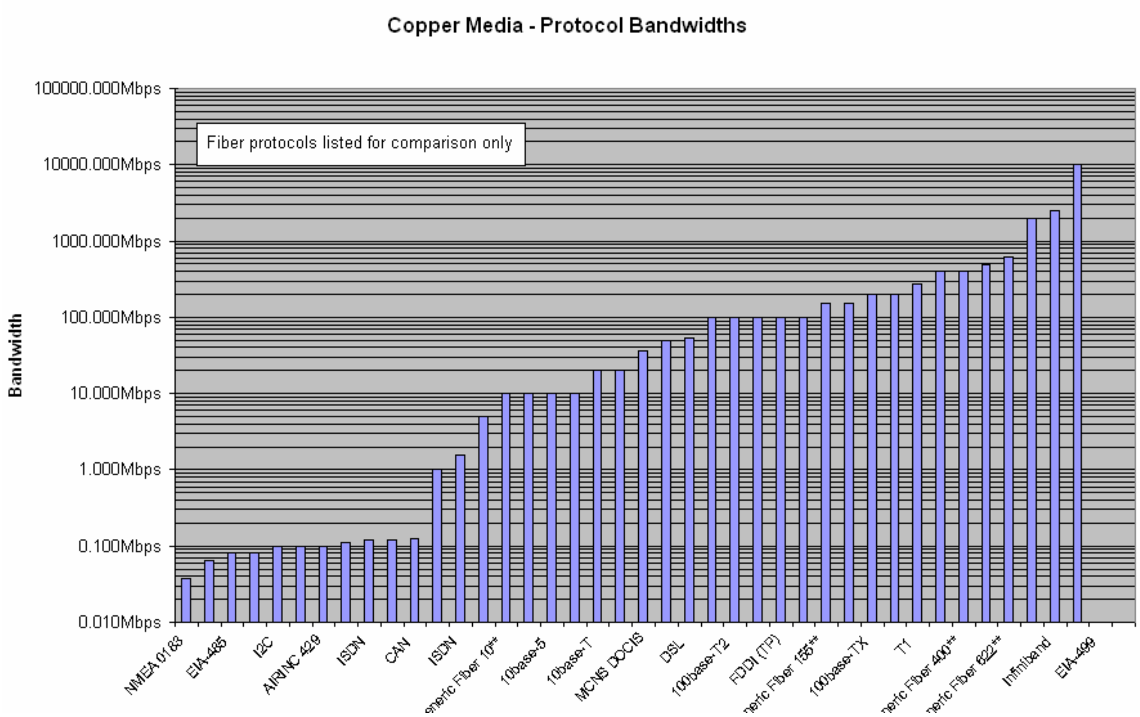


Figure 2: Chart comparing maximum bit rates achievable by different communication links.

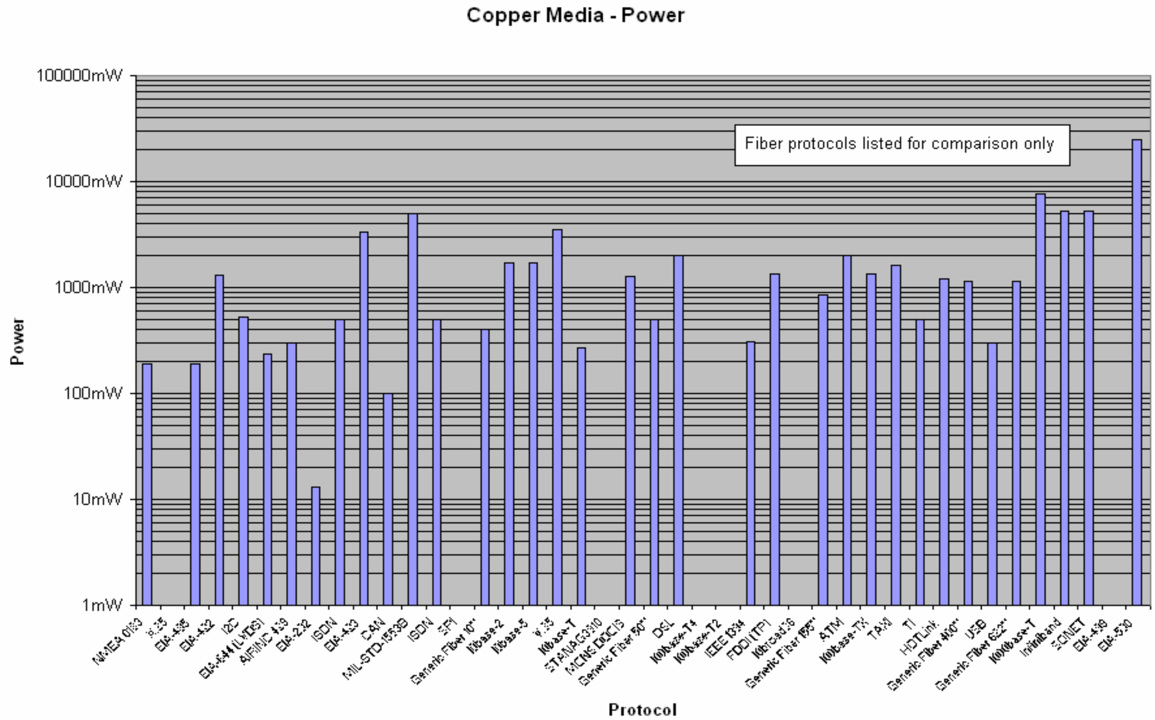


Figure 3: Chart comparing power consumption of different communication links.

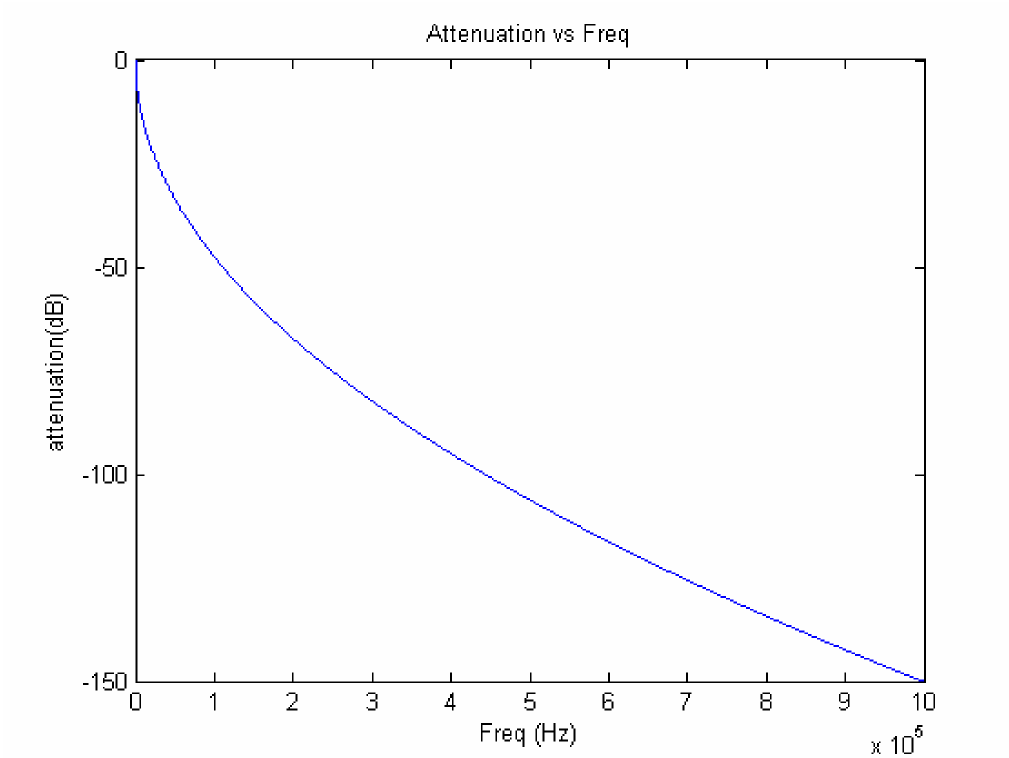
From these results it was concluded that fiber communication links were the only option that would satisfy the requirements for the MOOS communication link.

Unfortunately, the water tight connectors used to connect cables containing fibers in the harsh deep sea environment cost approximately $30,000 per pair, while the connectors containing only copper cost approximately $5,000 per pair. Considering that the average MOOS system uses 6 pairs, that amounts to a $150,000 savings per system.

Now that DSL is a fully developed technology it is time to reexamine the fiber vs. copper debate. There are many different DSL protocols available today, and while DSL was originally designed to operate at distances up to 18 kft (~5486m), there are now several DSL protocols that can operate at much further distances. The two considered were ADSL-Reach Extended (ITU: G.992.3 RE) and SHDSL (ITU: G.991.2). Both of these DSL protocols have power spectrum densities (PSDs) which have been shifted towards lower frequencies in order to avoid higher attenuation that affects high frequency signals. The attenuation over a twisted pair (TP) wire is given by Equation 1, where the cable gain (or negative gain = loss, attenuation, or insertion loss), HdB (in decibels), is given by a constant, K, times the distance, d (in km), times the square root of the frequency (in Hz).

$$HdB = -(K)(d)\sqrt{f} \qquad \text{(Equation 1)}$$

A graph of equation 1 is shown in graph 1 with values d=10 Km and K=0.015 (a typical value for a twisted pair).



Graph 1: Attenuation vs. frequency for a UTP at 10 Km

From this we can see that lower frequency signals will be subject to less attenuation. In general DSL modems can handle up to a 60 dB loss and still maintain a connection [3]. We can therefore see, from Graph 1, that our modems must operate below approximately 100 KHz. The PSD of ADSL-RE is shown in Figure 4. ADSL stands for 'asymmetric digital subscriber line', the 'asymmetric' refers to the fact that a larger bandwidth is allotted for downloading than is for uploading, this can be seen in figure 4. ADSL is designed to be used together with plain old telephone service (POTS) and therefore reserves 0-4 KHz, this can also be seen in Figure 4. As can be seen in Figure 4, ADSL-RE uses from 5-650 KHz, a bandwidth which is subject to too much attenuation for our application.

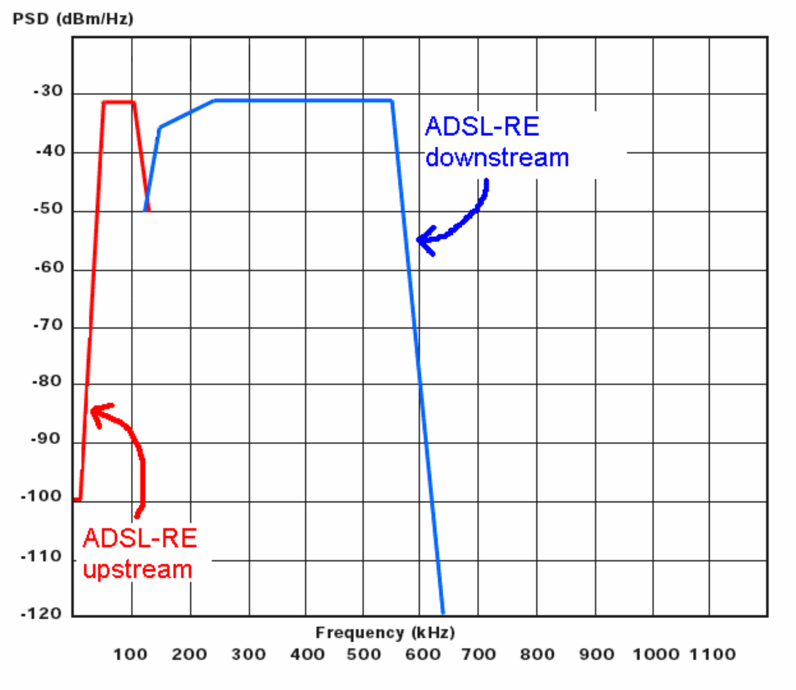


Figure 4: PSD of ADSL-RE.

SHDSL operates at a variety of speeds and adjusts its PSD in response to line conditions. The PSDs of SHDSL can be seen in Figure 5 for various speeds. SHDSL is not designed to be compatible with POTS and therefore can utilize the low frequency bandwidth from 0-4kHz. Operating at 256 KBps SHDSL fits our attenuation requirement to operate at frequencies below 100 KHz. As an added bonus SHDSL also allows for two customer premises equipment (CPE) modems to be connected directly together without the use of a Central Office (CO) DSLAM unit.

SHDSL offers a number of advantages over ADSL: Symmetric upload and download rates, two CPE units may be connected directly together, utilization of 0-4 KHz frequency range, and last, but most importantly, an overall frequency range under 100 KHz. For these reasons SHDSL was chosen over ADSL for hardware testing.

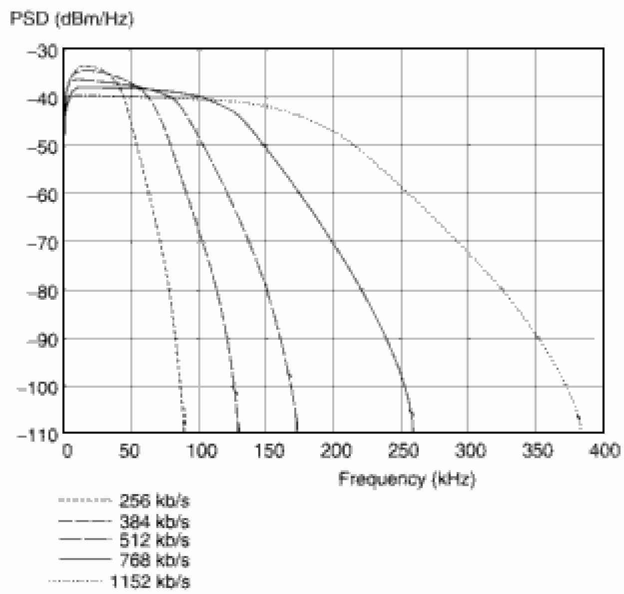


Figure 5: PSD of SHDSL.

MATERIALS AND METHODS

TESTING MATERIALS:

Digital Multi Meter (Fluke 179)
Oscilloscope (Agilent HP 54845A 1.5 GHz)
Spectrum Analyzer (HP 8562A)
Precision LCR Meter(Agilent 4284A 20 Hz – 1MHz)
0-50 VDC power supply (Agilent E3634A)
Breakout board for DSL communication line (Custom built see Schematic 1)
Balun transformers (North Hills 0315PB: 50-100ohm and 1307PB: 75-110ohm)
(2) Desktop computers (for modeling and setting up test link)
Software: Matlab, Simulink, FileZilla (ftp server), dos ftp client, QuickField, FEMM

TESTED MATERIALS:

(2) SHDSL modems (Net-to-Net SNE2000)
48-400 V power converter
400-12 VDC power converter
[1]. (1) 1000’ 4-conductor (2-pair) 22AWG Shielded Twisted Pair (STP)
[2]. (2) 500’ spools of RG59 coaxial cable + 1 pair 18AWG Unshielded Twisted Pair (UTP)
[3]. (2) 1.5 km 3-conductor cable (color: yellow)
[4]. (2) 4 km 2-conductor benthic cable (unbalanced, one wire at 40 ohms the other at 60 ohms)(color: orange)(optical-electric benthic cable manufactured by South Bay Cable)

[5]. (1) 4 km 5-conductor benthic cable (each wire has 127 ohms of resistance)(color: orange)(optical-electric benthic cable manufactured by South Bay Cable)

COMPUTER MODELING

Computer modeling of the complete system (except EM noise coupling) was done using Simulink. EM modeling software was investigated to model the EM noise coupling that could not be modeled by Simulink. Two finite element analysis programs, FEMM and QuickField, were looked into but not used due to time constraints. Hand transmission line models where also developed to characterize the different transmission lines.

The Simulink model was an extension of an ADSL model included as a demo with Simulink. The demo included a 256 channel ADSL transmitter and receiver, a typical channel response filter, and a BER output. The demo transmitter and receiver were unchanged but the channel and output were customized. The output was changed from a single BER output to a BER vs. SNR graph created by the BERTool within Simulink. The BER vs. SNR graph allows the system performance to be compared when different levels of noise are present, it also allows the system to be compared to theoretical results from a variety of standard modulations. The channel was changed in a number of ways: a transmission line model was added to model attenuation at long distances and to compare twisted pair lines to coaxial lines, an additive white Gaussian noise source was added allowing the BERTool to manipulate the SNR for testing, and finally a custom noise source was added to model the noise coupled to the communication cable from the power cable. An overview of the complete model is shown in Figure 6.

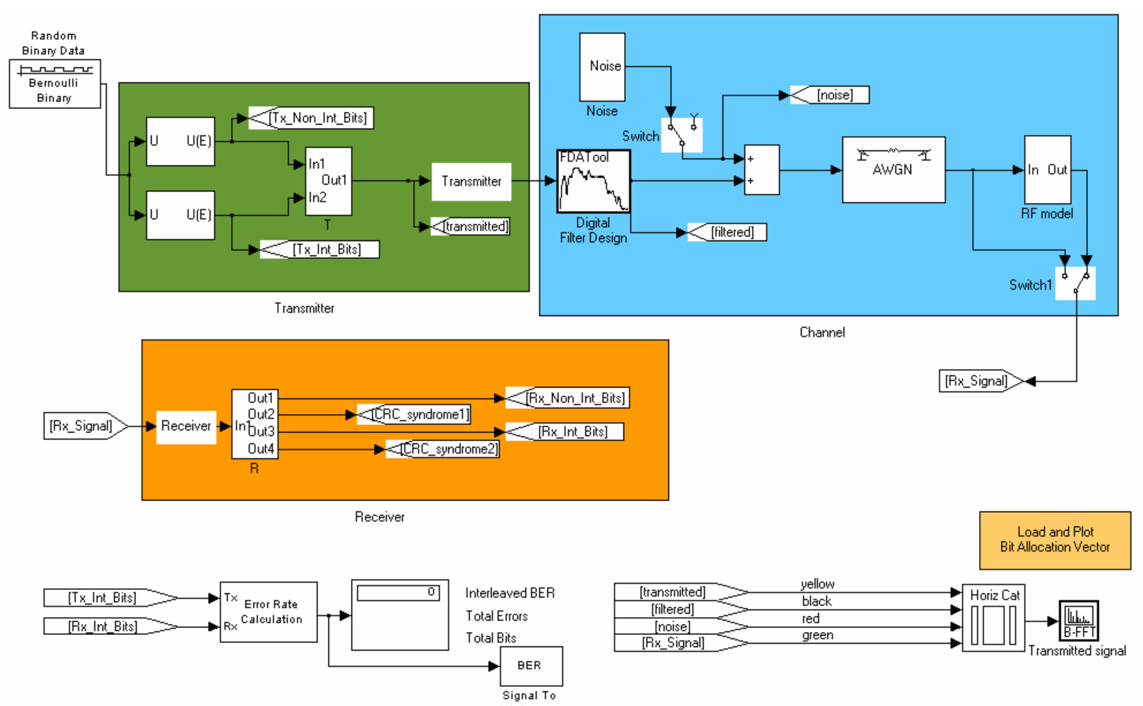


Figure 6: Simulink computer model used for modeling.

The details of the RF model and noise blocks are shown in Figures 7 and 8 respectively.

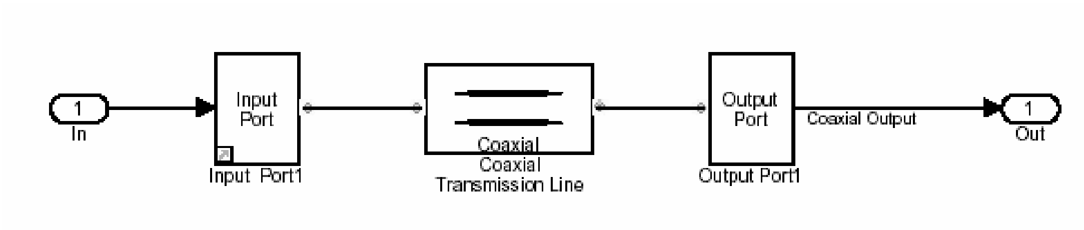


Figure 7: Simulink RF model details, coaxial TL shown here.

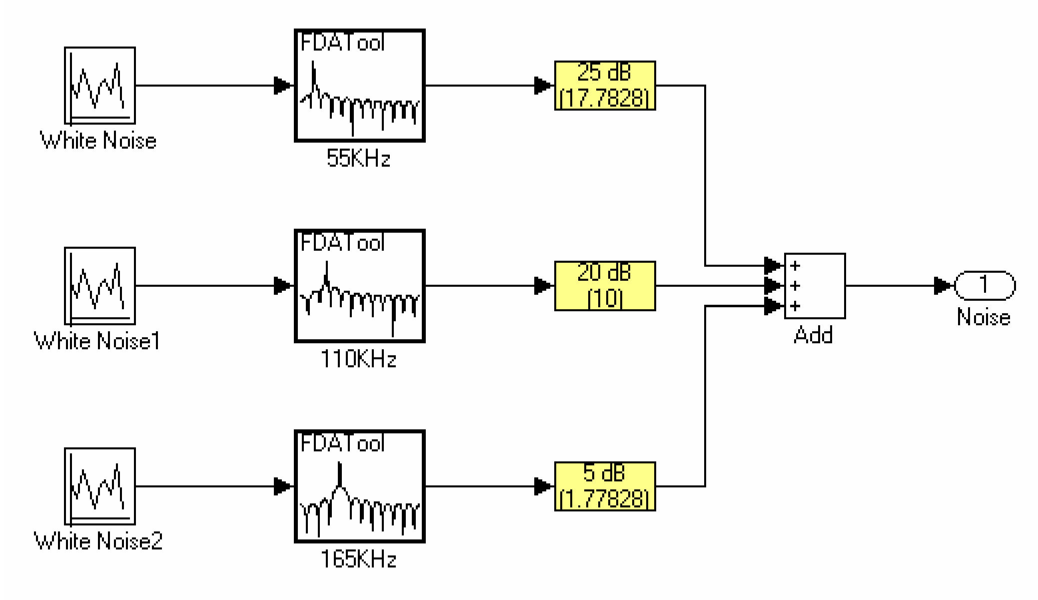


Figure 8: Simulink Noise block details.

Simulink was also used to compare the attenuation of different transmission lines. Compared were two-wire (equivalent to twisted pair) in both 26 AWG and 20 AWG gauges, and coaxial both RG-59 and RG-174. The model is shown in Figure 9.

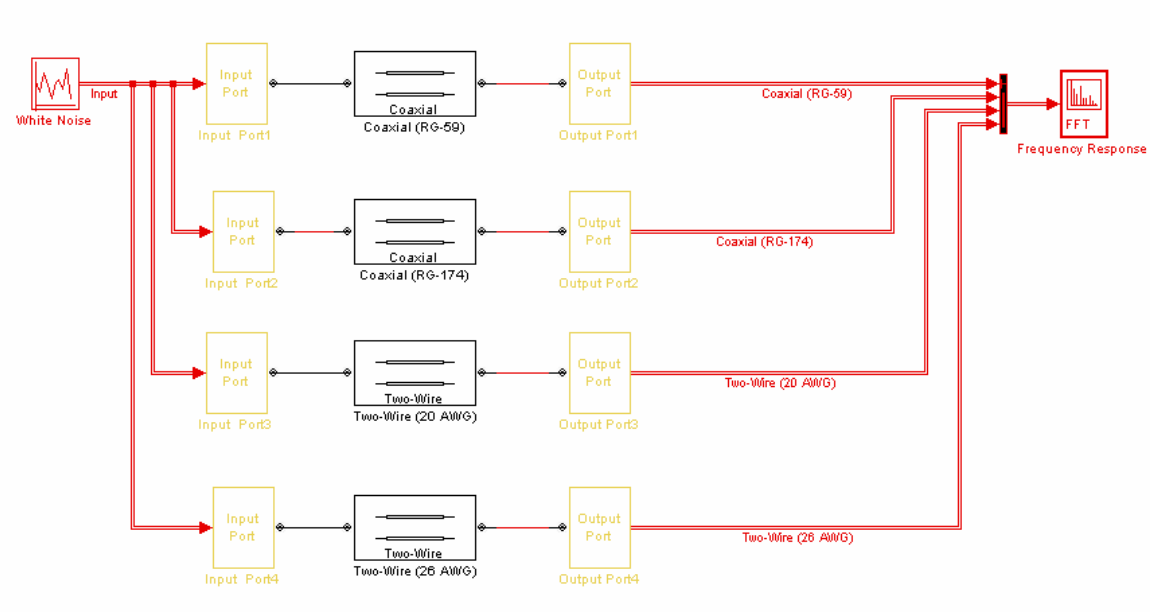


Figure 9: Simulink model used to compare attenuation on different transmission lines

TRANSMISSION LINE EFFECTS

The standard criteria to determine when transmission line affects must be taken into account is when the ratio of line length, L, to wavelength, λ, is less than 0.10.

$$\frac{L}{\lambda} \geq 0.10 \qquad \text{(Equation 2)}$$

ADSL and SHDSL operate on frequencies around 500 kHz which corresponds to a wavelength of 600 meters, our line length is 10 km, the resulting ratio is ~16.7, meaning transmission characteristics should be considered. This was modeled using TL blocks in Simulink. This also means care must be taken to match the impedances of the components of the communication link.

TESTING

Using the precision LCR meter, measurements of the inductance, capacitance and resistance were taken of all the cables listed except for the 4km benthic cable. The 4 km benthic cable has five 20 AWG copper conductors, but at the waterproof seals at both ends of the cable the 5 conductors are merged into 2 conductors, which where used for the power system. For the power system, the fact that one conductor is actually 3 conductors, while the other conductor is actually 2 conductors, resulting in an unbalanced pair, does not matter. But for the communication system it does and a model of this cable would not represent a realistic option.

In an ideal world the 48-400 V and 400-12 VDC power converters operate on DC voltage alone but in practice there are AC components as well. These AC components are coupled into the communication line and have the potential to interfere the DSL signals. To test the frequencies and magnitudes of the AC components, a spectrum analyzer was connected to the communication lines while power was being transferred through the power lines, this allowed for the characterization of the PSD being coupled from the power lines onto the communication lines.

The peak-to-peak voltage of the noise coupled onto the STP and coaxial cables from the power cable was measured using an oscilloscope.

CABLE CONFIGURATIONS

The cables lengths used for bit rate testing were 1.5 km, 3km, 4km, 5.5km, 7km, 8km, 9km, 11km. Some of these cables were continuous lengths of cable (1.5km, 4km), some were two identical spools spliced together (3km, 8km), and the rest were combinations of two different cables spliced together. The 4km spools are unbalanced as mentioned before and therefore the testing performed on them may be inaccurate. The 1.5km spools have more insulation than the actual communication cable would have and therefore may be inaccurate. The combination of the 1.5km spools and 4km spools creates impedance mismatches and therefore the data may be inaccurate. Because of the afore mentioned cable problems tested bit rates represent a lower limit and could be higher with properly configured cables.

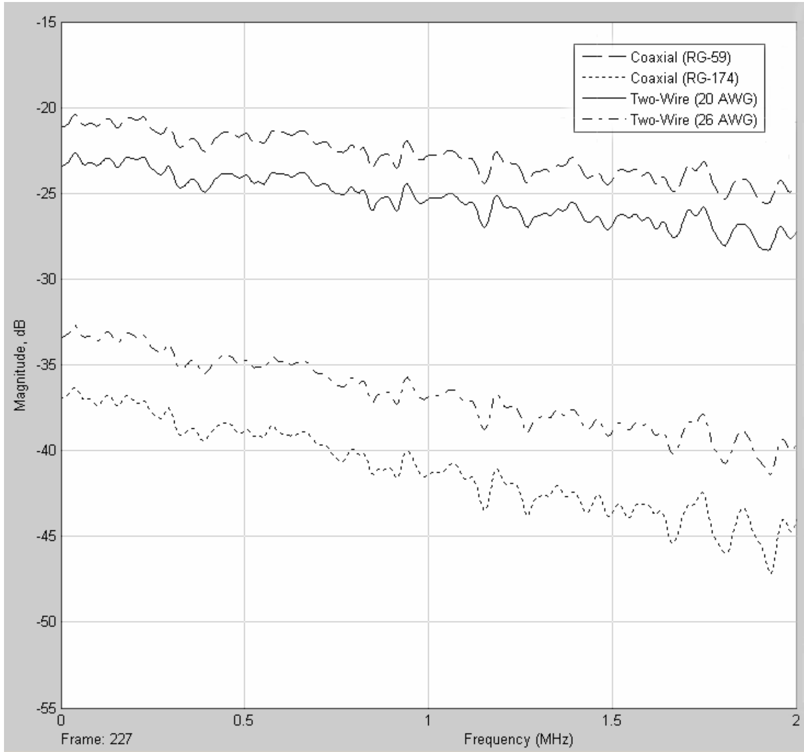
SHDSL DISTANCE PERORMANCE

The SHDSL modems where tested at a number of different lengths through different cable types. The results are shown in Table 2 and Graph 5. Different cable types where used in combination for some lengths, this is undesirable but was necessary since there was a limited supply of long lengths of cable for the tests (see the previous section "CABLE CONFIGURATIONS" for information on each particular cable).

RESULTS

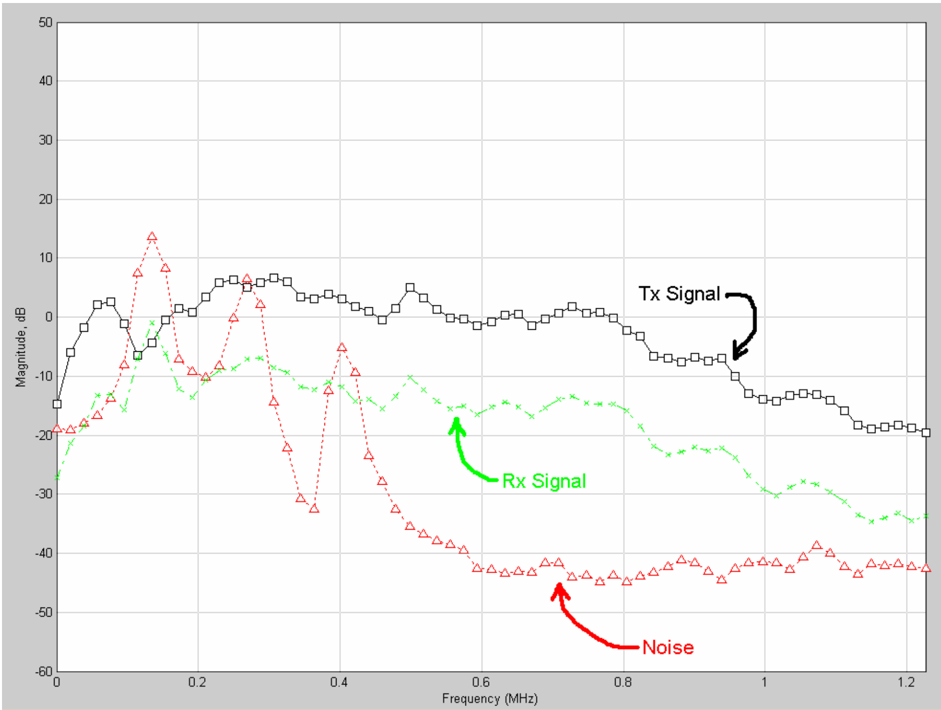
MODELING RESULTS

The RF TL model in Simulink, shown in Figure 9, was used to compare the dB loss in different TP and coaxial cables, the resulting out put can be seen in Graph 2. From Graph 2 we can see that while RG-59 coaxial cable performs the best, 20 AWG TP performs better than RG-174.

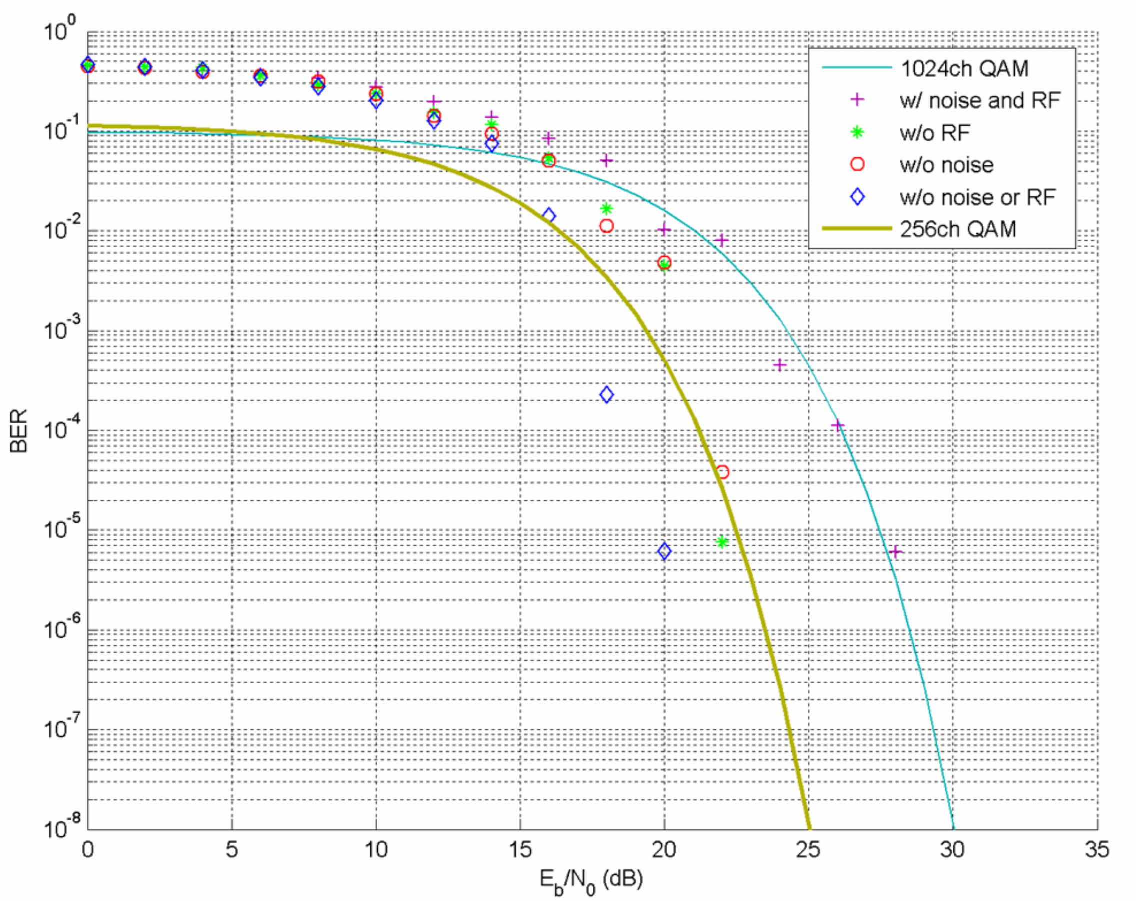


Graph 2: Attenuation of twisted pair compared to coaxial cable verse frequency.

The Total PSD of the Simulink model is shown in Graph 3. The transmitted signal has already gone through a shaping filter that represents a standard transfer function for a TP. Looking at the received signal you can see the effects of attenuation, the received signal is at a lower magnitude than the transmitted. Barely noticeable is the fact that the attenuation is greater at higher frequencies. Also where the noise is strong enough to cross the transmitted signal it can be seen in the received signal



Graph 3: PSD of Simulink model, notice noise interference and attenuation in received signal.



Graph 4: BER vs. SNR output of Matlab model, solid lines are theoretical results from standard modulation schemes shown for comparison.

HARDWARE RESULTS

The peak-to-peak voltage induced on the STP and coaxial cables from the power cable was measured with the oscilloscope. One end of the cable attached across the probe of the oscilloscope while the other end was attached to the cable’s characteristic impedance (100 ohms for the STP and 75 ohms for the coaxial). Coax=1.04 volts STP=2 volts

With the DMM connected in series between the SHDSL modem power jack and the 120 VAC-5VDC power adapter (which actually put out 4.96 volts), the measured current was 0.65 amps when the modem was idle, and 0.662 amps when transmitting and receiving data. At 4.96 volts this corresponds to a power usage of 3.2 watts when idle, and 3.3 watts when transmitting and receiving data.

The PSD voltage peaks induced on the 468’ TP communication cable from the power cable with 30W load as measured by the spectrum analyzer are seen in Table 1. Figure 9 is a screen shot of the fundamental noise peak displayed on the spectrum analyzer screen.

Length	456 feet				321 feet			
Shielding	shield on		shield off		shield on		shield off	
Termination	OC	100ohm	OC	100ohm	OC	100ohm	OC	100ohm
Freq(kHz)								
52	0.55	0.39	290	180	0.27	0.19	315	205
108	5.4	5.1	162	137	3.3	2.5	222	163
165	1	1.5	26	53	1	0.9	55	50
219	0.25	0.35	25	14	0.2	0.26	10	7
275	0.2	0.14	24	16	0.3	0.2	5	5
330	0.1	0.02	29	21	0.11	0.15	8	6
385	0.15	0.12	19	11	0.25	0.2	11	9
440	0.3	0.2	12	7	0.35	0.22	18	12
499	0.33	0.19	11	7	0.3	0.2	15	10

Table 1: Noise coupled, in mV, as measured with spectrum analyzer, without DC block, using 50ohm-100ohm Balun transformer, from one twisted pair carrying 400V [from 48-400V converter to 400-12VDC converter with 5ohm load(delivering ~30W)] with shield floating, to other twisted pair with separate shield (attached as noted), but within same jacket, terminated as noted. Both twisted pairs are 22AWG.

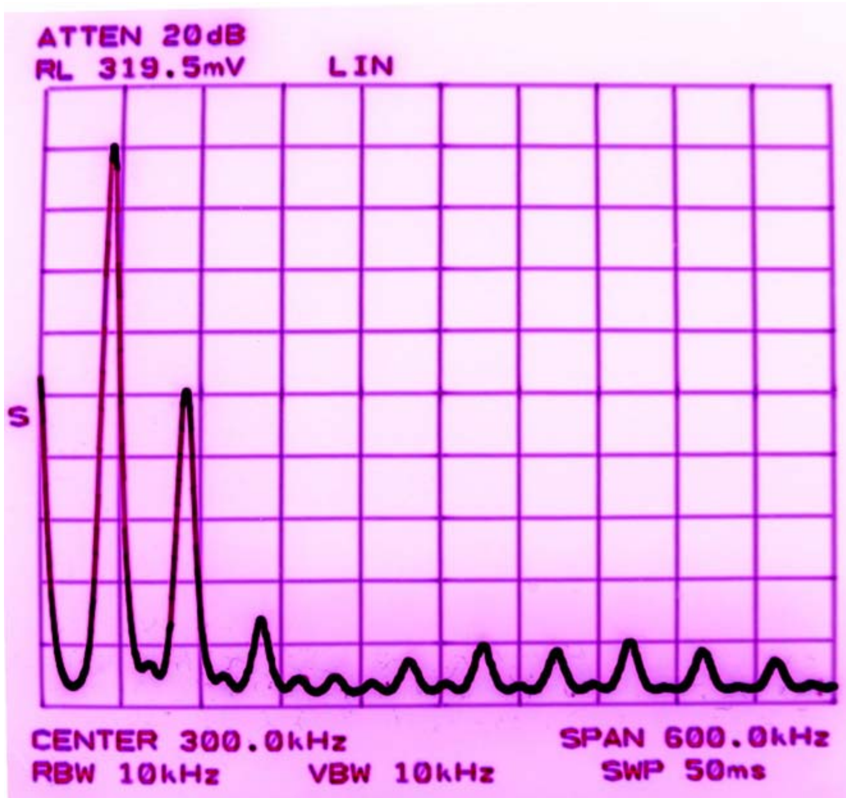
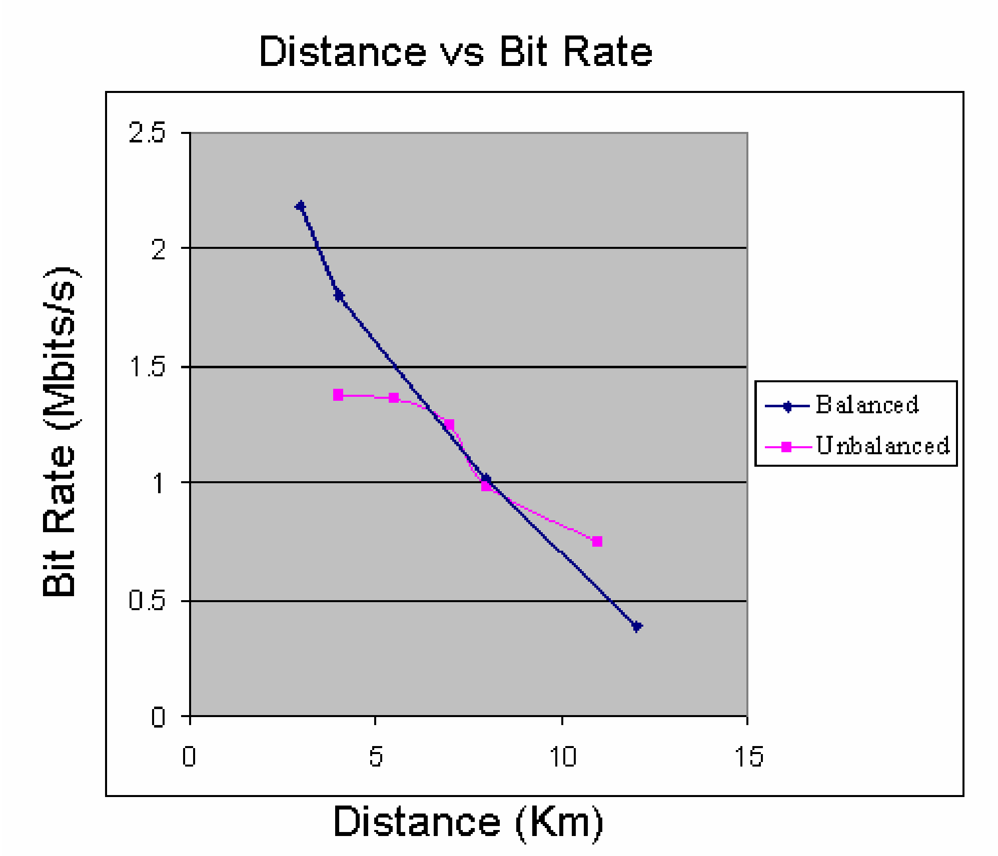


Figure 9: A representative screen shot (from the spectrum analyzer) of the noise being coupled onto the communication cable. This is from the 456 foot, shield off, OC, test in the table above

The bit rate of transmission over the various cable types and lengths is organized in Table 2. This data is graphed versus distance in Graph 5.

Km	bal/unbal	speed(Mbits/s)	loop res(ohms)	Cable config(see Materials list)
3	bal	2.184	128	3-3
4	bal	1.8	254	5
4	unbal	1.37	102	4
5.5	unbal	1.36	166	4-3
7	unbal	1.247	230	4-3-3
8	bal	0.983	204	4x4
8	unbal	0.982	204	4-4
9.5	unbal	N/A	268	4-4-3
11	unbal	0.743	329	4-4-3-3
12	bal	0.383	460	5-4x4

Table 2: Bit rates, in Mbits/second, at the various tested lengths.



Graph 5: Tested bit rates verse distances.

The present optical-electric benthic cable manufactured by South Bay Cable has 20 AWG copper conductors which are specified for no more than 10.5 ohms per 1000 feet. At 10 km this would correspond to a resistance in one conductor of 344 ohms, or a loop resistance of 688 ohms. As can be seen in Table 2, the loop resistance for both the 11km and 12km tests are much less than this. This is because cable number 4 contained multiple conductors spliced together.

DISCUSSION

The SHDSL modems tested seem to be able to overcome a number of problems associated with many copper based communication links. From the modeling alone the maximum link distance seems to be much less than 10 Km. This is probably due to limitations in the model and advances in DSL not incorporated in the model. The model is none the less important as it allows us to make important comparisons between other variables, such as cable type and noise type. Another major obstacle overcome by the SHDSL modems is the unbalanced cable configuration used in most of the tests (as described in "CABLE CONFIGURATIONS" previously). The line drivers in the DSL modems are designed to be used over a balanced cable, and the unbalanced cables used no doubt had an affect on the performance of the system.

Since an ideal test cable was not available we must deduce the performance from the available tests. While a connection was made at 12 km the wire was not a constant gauge through out. This would degrade performance due to impedance mismatches and improve performance due to a lower overall impedance of the loop. The resistance of each wire was 230 ohms instead of the 413 ohms it would have been for a 12km run of 20 AWG gauge wire. When additional resistance was added to the end of the cable the modems would not connect. However, the modems would connect through a 413 ohm resistor. This implies that the modems could connect if the wire had an impedance of 413 ohms, but possibly the combination of cables and resistors resulted in too many impedance mismatches. During testing problems with the second lowest speed (528kBps) were discovered. In many of the longer distanced tests the modems would not connect when set to 528 KBps, but would connect at the next few higher settings. Also the ‘adaptive’ mode would sometimes not connect even when other speed modes would, and when the adaptive mode would connect it would sometimes not connect as fast as other modes. The DIP switches controlling the speed settings were tested and seemed to be operating correctly. Therefore one must assume that either one or both of the modems have a defect or that the modem has a design flaw. This is unfortunate because the lowest speed setting is 400kBps but the modems are supposed to be able to operate down to 144kBps in ‘adaptive mode’. Hopefully future modems will have an ‘adaptive’ setting which operates more reliably.

A twisted pair cable presents a number of advantages over coaxial: the line drivers on most commercial DSL modems is set up for a balanced TP, TP is cheaper than coaxial cable, in a coaxial cable noise would be coupled more strongly in differential mode, and from the Simulink results attenuation seems to be better on a realistic TP option than the coaxial option.

The noise is caused almost entirely by the 48-400V converter. The fundamental noise peak is at ~55 kHz which is the switching frequency for the inverter on the 40-400 converter board. Other noise peaks are at the harmonics of this: 110, 165, 220, 275 kHz, etc. In some tests the 55 kHz peak was lower than the 110 kHz possibly due to shielding of the 55 kHz peak.

CONCLUSIONS/RECOMMENDATIONS

DSL has matured enough since the data presented in Figures 1, 2, and 3 ruled it out as a possible candidate that it should be reconsidered as an option when constructing future MOOS systems. The fiber links do provide a much higher bit rate than that of the DSL links, but since the data must be sent through a 7200 baud satellite modem this advantage is of no use unless high speed inter-node processing is being used or the satellites bit rate is significantly improved.

Considering that an approximate $150,000 could be saved in just one MOOS system using copper instead of fiber, the cost of developing a DSL MOOS seems easily justifiable.

A number of steps should be taken to implement DSL communication in the MOOS project in the future. First a cable with a copper communication pair needs to be obtained. This alone may prove to be sufficient to create a link for the present SHDSL modems that could then be deployed with modifications to the modems allowing them to be integrated into the MOOS mooring controller chassis and allowing them to be powered on and off remotely. Beyond this, building a more custom DSL board could offer a number of benefits to connection distance and speed. Modification of the 48-400 converter boards could reduce noise also allowing for an increase in connection distance and speed.

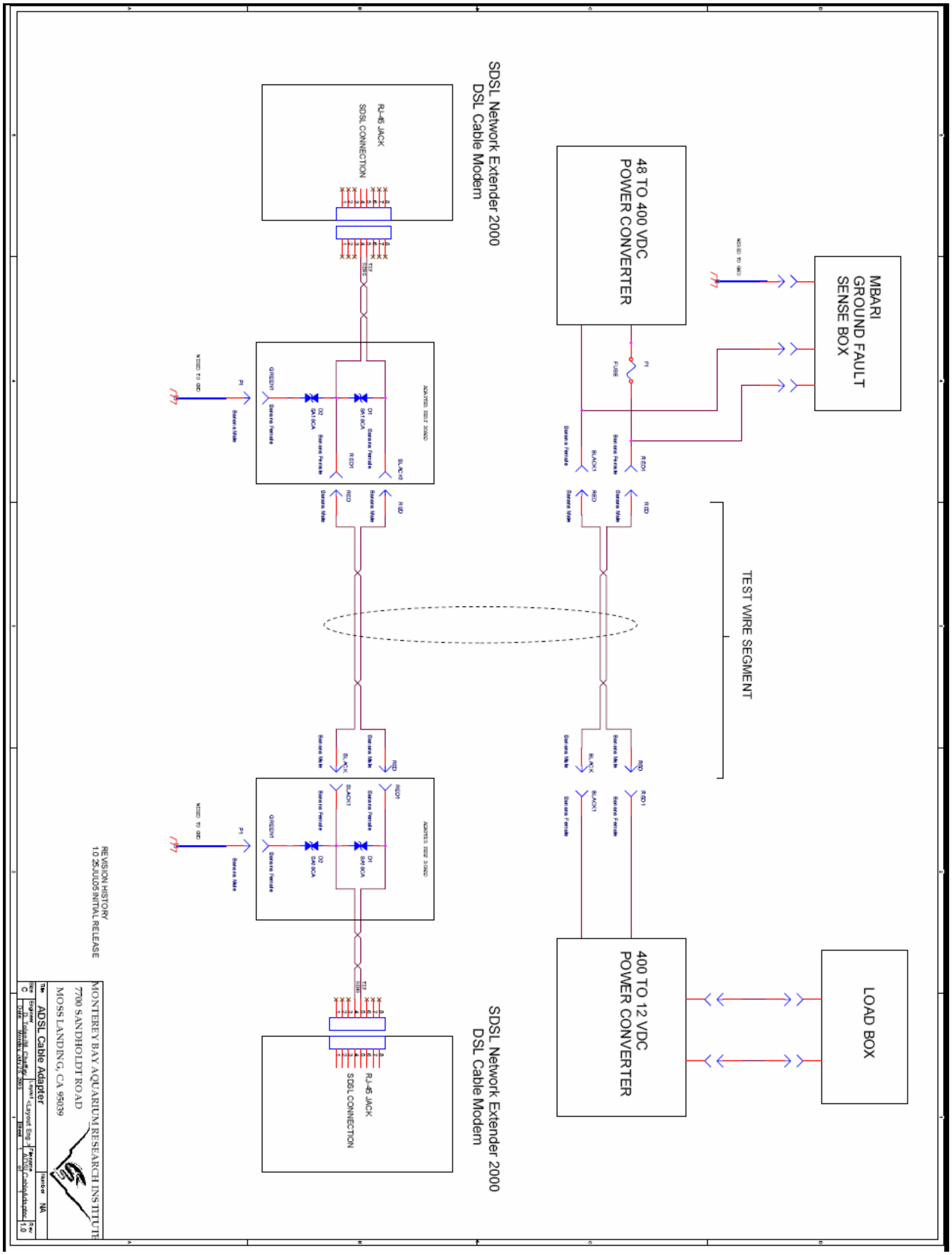
In order to further test the abilities of DSL, and specifically SHDSL, in the MOOS project, a new cable needs to be specified. From the data collected through this project I believe an appropriate specification would include a 20 AWG shielded twisted pair (STP) with a drain wire. The tested SNE2000 SHDSL modems would likely connect in their '400 kBps' mode through 8km of this cable alongside the 400 volt power cable. However, it would be desirable to test SHDSL modems whose 'adaptive' mode is functioning more reliably than the SNE2000's used in these tests. By putting the modems in the '400 kBps' mode you are trying to force them to connect at a higher speed than may be possible.

If the modems were to be specially built for the MOOS project, a more optimal design could be achieved. Using a SHDSL DSP (which would include the framer, encoder, decoder, and PAM engine) along with an analog front end (AFE) (which would include the A/D converter, D/A converter, shaping filter, gain control, and line driver), a SHDSL modem could be custom built for the MOOS system. One of the benefits of this would be the ability to have a higher output power since we do not need to worry about near end crosstalk (NEXT) which limits the SHDSL output power spec to 13.5dBm [3]. For instance, Texas Instruments makes an AFE, the AFE1230, which can output 14.5dBm onto a 135 ohm line or can be connected to their OPA2677 line driver for an output of 17dBm. This could improve problems with attenuation and noise interference and may allow for a higher bit rate to be achieved. Using a custom board would also allow the line driver to be matched to the cable's impedance.

Some sort of power conserving design would have to be implemented since the modems draw 3+ volts even in an idle state. Mark Chaffey has suggested that a voltage offset on the communication line could be used to control power to the modems allowing for them to be put in 'sleep' mode when not in use.

Currently there is only a first order low pass filter on the output of the 48-400 converter boards. While most noise from the power supply is common mode which is rejected by the differential amplifiers in the modems, some does appear as differential mode. Therefore, cascading another RL low-pass filter onto the output of the 48-400 converter board may help.

SHDSL has performance characteristics that make it an excellent candidate for use as a communication protocol for the MOOS system. Most notably an adaptive bit rate and PSD mask which can operate at frequencies below 100 KHz. Whether commercial SHDSL modems are modified to be included in the MOOS mooring, or a new SHDSL modem is built from chipsets, the first step to further test SHDSL would be to order cables specifically designed for copper based communication.



Schematic 1: Test setup showing power and communication connections and DSL breakout board

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