Modem, DSL and Powerline technologies

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1 Modulation/Demodulation techniques

The modem was invented for North Ameriacan air defense in the 1950's. It was used to communicate data over the public switched telephone network (PSTN). Modem stands for modulate/demodulate. The digital signal has to be modulated to an analogue frequency that the PSTN can carry (0-3400 Hz), so different modulation techniques had to be invented. In 1962, the first commercial modem was manufactured by AT&T. It was called Bell 103 and was the first modem that used full-duplex transmission, frequency shift keying (FSK) modulation and had a speed of 300 bauds[1]. Other modulation techniques are called quadrature phase shifted keying (QPSK) and quadrature amplitude modulation (QAM). QAM modems can transmit 9600 bauds or more.

It is said that the physical limit for analogue communication has been reached with modems at 56 kbits/sec, known as 56k, which were invented by Dr. Brent Townshend in 1996. They use a much more complicated encoding technique than QAM and also benefit from the fact that most modern PSTN's are digital. Internet Service Providers (ISP's) have direct access to these digital backbones. Therefore there is only one digital to analog modulation at the consumers side. The upload is limited by the modulation and signal noise on the cable, but reaches up to 36k. The download reaches up to 56k, because the data stays digital all the way to the telephone exchange, which is, in most cases, not far from the consumer. We will see later, that the distance from modem A to modem B is the most important factor for the transmittable datarate.

All modulation techniques of these modems are downward compatible. So even with a 56k modem you can still connect to the Bell 103, at 300 baud.

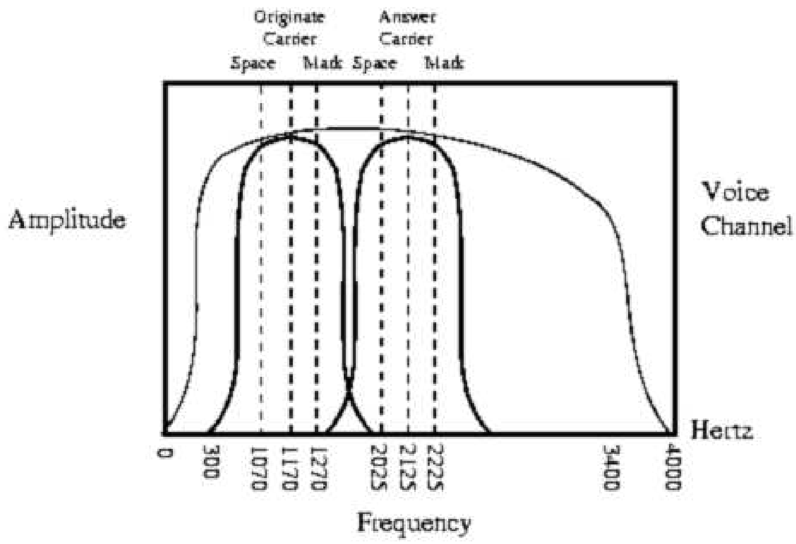
Nowadays there are not only modems for telephone lines, but cable-, powerline-, dsl- and much more different types of modems. But they all use one of the following modulations/demodulations with only slight changes.

1.1 Single-carrier techniques

Frequency Shift Keying (FSK) is the frequency modulation of a carrier to transmit digital data. For simplex operation (A sends data to B, but B cannot send data to A at the same time) a carrier signal at 1170 Hz is used. If A wants to send a 1 the carrier is modulated plus 100 Hz, to 1270 Hz. If he wants to send a 0 it is modulated minus 100 Hz, to 1070 Hz. B receives the changes of the frequency and can decode them back to digital data.

For full-duplex operation a second carrier is needed. On this carrier the same modulation technique is used by B, to send data to A, at a higher frequency. The carrier is at 2125 Hz, a 1 is sent with 2225 and a 0 with 2025 Hz. The two carriers can be easily seperated using a high/low-pass filter.

[1] baud=bits per second



FSK transmits one bit per frequency change. If a FSK-modem has a datarate of 2400 baud it means that it can transmit 2400 bits per second, meaning 2400 changes of the frequency per second. The resulting carrier signal has to be above 2400 Hz, otherwise the datarate cannot be achieved. Due to the limited range of the PSTN there is no place for a second carrier for full-duplex operation for modems higher than 2400 baud, without running into crosstalk difficulties. That is why the fastest available FSK-modems were limited to 2400 baud.

Quadrature Phase Shifted Keying (QPSK). As we have seen, the carrier signal of a telephone line is limited to 3400 Hz. Another approach to transmit more than 2400 baud is not to modulate the frequency but to use an encoding technique for modulating the phase of the carrier signal. The easiest procedure is know as QPSK.

QPSK uses a carrier signal at 600 baud plus the following encoding:

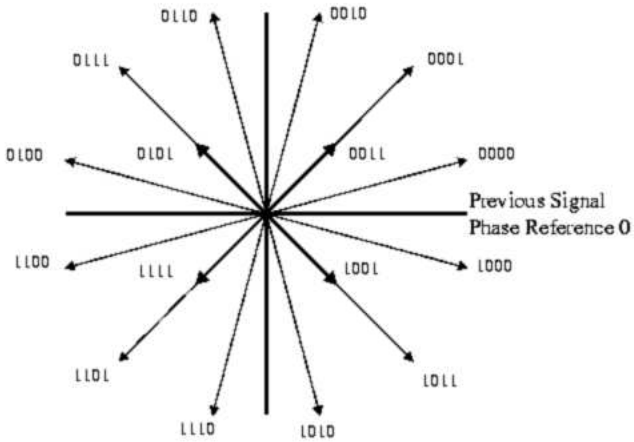
bits to send	phase shift
01	0°
00	90°
10	180°
11	270°

With this modulation 2 bits are sent per change in the phase of the carrier signal. a little calculation gives: 2 bits·600 bauds = 1200 bps.

The bits can be easily mapped to the frequency samples by using inverse fourier transform. On the other side the bits can be recoverd by a normal fourier transform. The carrier at 600 bauds leaves enough space for a second carrier to facilitate full-duplex operation.

Quadrature Amplitude Modulation (QAM). The physcial limit for QPSK is not reached at 1200 bauds. it can be increased by using higher carrier signals and more phase shifts. Additionally the amplitude of some signals can be modulated. This procedure is known as Quadrature Amplitude Modulation (QAM).

16-QAM, as an example, uses 12 phase angles, 4 of them with 2 amplitude values. With this modulation 16 values (4 bits) can be tranmitted at every baud change. This gives: 4 bits·2400 baud = 9600 bps.



1.2 Multi-carrier techniques

Multicarrier techniques use an aggregate amount of bandwidth and divide it into subbands, thereby yielding multiple, parallel, narrower channels. Each subband is encoded using a single-carrier technique (such as QAM), and bit streams from the subbands are bonded together at the receiver. Important examples of multicarrier techniques include orthogonal frequency division multiplexing (OFDM), which is used in Powerline technologies and discrete multitone (DMT), which can be found in ADSL and VDSL. Detailed descriptions of these can be found in the corresponding chapters in this paper.

2 DSL technologies

Digital Subscriber Line (DSL) is a networking technology which operates on ordinary phone-lines to provide a high-speed network-connection. There is no special network-cable needed, which makes DSL a cheap alernative to many classical methods.

There are many different kinds of DSL: ADSL, HDSL, SDSL, VDSL, etc. This is the reason why the term xDSL is used. Using ADSL/VDSL one can simultaneously use data and telephone services.

DSL doesn't allow dial in to any other DSL-modem, like regular modems do, but provides much higher datarates on short-range connections (up to 5.5km) of one piece of ordinary twisted pair copper cable like from the home to the switching center of the telco (local loop). This means that it can be used as a technology to provide users with high-speed internet-connections at low cost.

Unlike ISDN, which is also digital but travels through the switched telephone network, DSL provides 'always-on' operation. The only reason one has to 'dial in' is accounting. At the telco central office, DSL traffic is aggregated in a unit called DSL Access Multiplexor (DSLAM) and forwarded to the appropriate ISP or data network.

2.1 Different Types of xDSL technologies:

This list is not complete, it contains only the most important ones.

DSL Digital Subscriber Line technology, on which all the variations in this listing are based.

ADSL Asymmetric DSL, with a larger portion of the capacity devoted to downstream communications, less to upstream.

RADSL Rate Adaptive DSL is a version of ADSL that adjusts speeds based on signal quality. Many ADSL technologies are actually RADSL.

HDSL High-bit-rate DSL, a technology for the business market in commercial operation several years, using two wire pairs with 1.5 Mbps each way.

SDSL Symmetric DSL is a variation of HDSL using only one wire-pair, typically with about half the speed each way when compared to HDSL.

VDSL Very-high-bit-rate DSL which provides, with speeds up to 52 Mbps, but for only short distances, the highest rates of transmission.

2.2 Splitters

A splitter is a small passive device that captures the first 4 khz of frequency and splits them off for phone use, the rest of the data is passed onto the DSL equipment. The splitter is the first device a DSL line meets when it arrives at the users premises. Splitters are used with ADSL and VDSL lines. For SDSL and HDSL, there is no voice band available, so there is no need for a splitter.

2.3 Modulation techniques

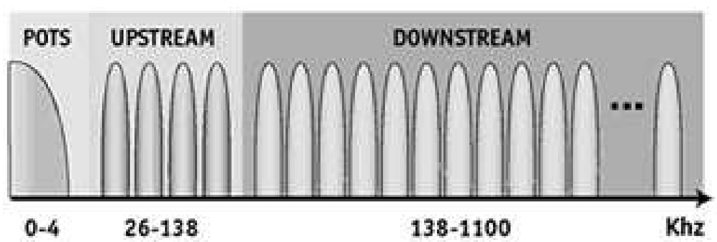
For ADSL there are two modulation methods in use, one called Carrierless Amplitude/Phase (CAP) and one called Discrete Multi-Tone (DMT).

CAP is a version of QAM in which incoming data modulates a single carrier that is then transmitted down a telephone line. The carrier itself is suppressed before transmission (it contains no information, and can be reconstructed at the receiver side), hence the adjective 'carrierless'. CAP is considered inferior to DMT.

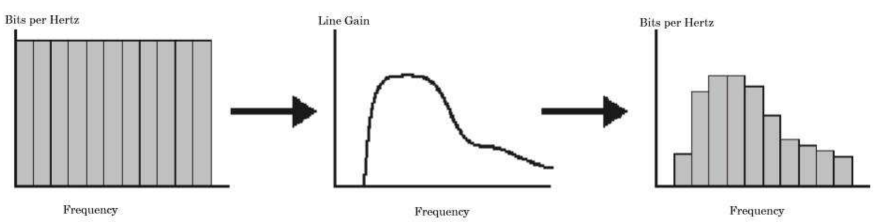
Most modern ADSL- and all VDSL-modems use DMT, whereas HDSL- and SDSL-hardware is using another method, called Two Binary, One Quaternary (2B1Q).

Discrete Multi-Tone (DMT, ANSI T1.431) is a method which separates a DSL signal so that the usable frequency range is separated into frequency bands (or channels) of 4.3125 kHz each (0 to 60 kbps). Most times more bands are used for downstream, less for downstream.

DMT uses the fast Fourier transform (FFT) algorithm for modulation and demodulation. Within each channel, modulation uses quadrature amplitude modulation (QAM). When two DSL-modems (or a modem and a DSLAM) connect, they test each channel and calculate its signal to noise (S/N) ratio. More bits are assigned to channels with a high S/N ratio. By varying the number of bits per symbol within a channel, the modem can be rate-adaptive.



The number of bits per channel depends on the properties of the line (Line Gain) as it can be seen in the following illustration. Subbands, which have high noise problems, can be avoided to guarantee a proper transmission.

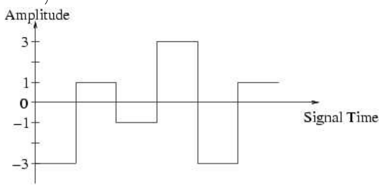


The theoretical limit of ADSL is calculated by 256·60 kbps=15.36 Mbps. In reality lines with 768 kbps to 9 Mbps are offered.

Two Binary, One Quaternary (2B1Q, ANSI T1.601) represents a straightforward signal type that has two bits per baud arranged as one quaternary or four-level pulse amplitude modulated scheme. It has four levels of amplitude (voltage) to encode two bits. Because there are four voltage levels, each level translates to two bits per symbol.

Bits	Voltage Level (Amplitude)
00	+3
01	+1
10	-1
11	-3

The following image shows the encoding of the 12 bits 110110001101 in six symbol times. Thus, two bits are transmitted for each symbol time.



It is possible to increase the bit rate of a wire or of a wireless (where 2B1Q can also be used) channel either by increasing the symbol rate of the transmission or by increasing the number of bits per symbol. 2B1Q modulation produces two bits per symbol and hence can transmit twice the data of another modulation scheme that transmits one logical bit per symbol. If you want more bits per symbol, more voltage levels are needed. To encode k bits per symbol time, you need 2^k voltage levels. As speed requirements increase and more voltage levels are used, it becomes increasingly difficult for the receiver to discriminate among these voltage levels with consistent precision.

However, 2B1Q has the advantage of being a well-understood modulation scheme that is relatively inexpensive and robust against the kind of interference observed in a telephone plant, where its use is very appropriate.

2.4 Specifications

	ADSL	HDSL	SDSL	VDSL
Bits/second	768kbps-9Mbps down 16-640kbps up	1.5 or 2Mbps	144kbps-1.5Mbps	13-52Mbps down 1.5-2.3Mbps up
Mode	asymmetric	symmetric	symmetric	asymmetric
Copper pairs	1	2	1	1
Range (˜)	3.7 to 5.5km	3.7km	3km	1.2km
Signalling	analog	digital	digital	analog
Line Code	CAP/DMT	2B1Q	2B1Q	DMT
Frequency	up to 1-5MHz	196kHz	196kHz	up to 12MHz
Bits/cycle	varies	4	4	varies

2.5 Experiments

We did some Experiments with the Ethernet over VDSL modems CPE-EOV/N and CPE-EOV/L by MRV Communications, Inc. These two are basically the same. They only differ slightly in that the /N model should be used at the customers, the /L model at the providers side. We couldn't find a technical reason for this difference in names. Both are full duplex 10 Mbps VDSL-modems which work on a max. distance of 1.2 km (manufacturer info).

The line speed was measured with the networking benchmark-tool netperf on a 6 m copper line with one pair of leads:

- /L to /N:
```
TCP STREAM TEST to 192.168.1.41
Recv   Send   Send
Socket Socket Message Elapsed
Size   Size   Size    Time    Throughput
bytes  bytes  bytes   secs.   10^6bits/sec
87380  16384  16384   10.01   10.73
```

- /N to /L:
```
TCP STREAM TEST to 192.168.1.44
Recv   Send   Send
Socket Socket Message Elapsed
Size   Size   Size    Time    Throughput
bytes  bytes  bytes   secs.   10^6bits/sec
87380  16384  16384   10.21   10.54
```

This simple experiments were repeated many times, but show always likewise results. The throughput is always little above 10 Mbps to both sides. We didn't have much longer cables to test the hardware under harder circumstances.

3 Powerline Networks

Powerline-Networks are slightly different than other Computer-Networks. They do not need any special infastructure, like Ethernet for example. The Powerline technology is just using the power-cabeling, which is used for supplying nearly every building in the developed world.

There are two different types of Powerline:

1. 'access'
2. 'in-home'

The 'access' variant is mainly used for covering the 'last-mile' of Internetaccess, just like ADSL. The other one makes it possible to quickly implement inhome communications. As the first method seems to be obsolete due to other faster and cheaper inventions, like xDSL, we won't cover this topic here.

This seems to be a nice idea, but if you use a media which is not designed to be used for data communication, you have to deal with several technical obstacles:

1. attenuation
2. wire quality
3. noise

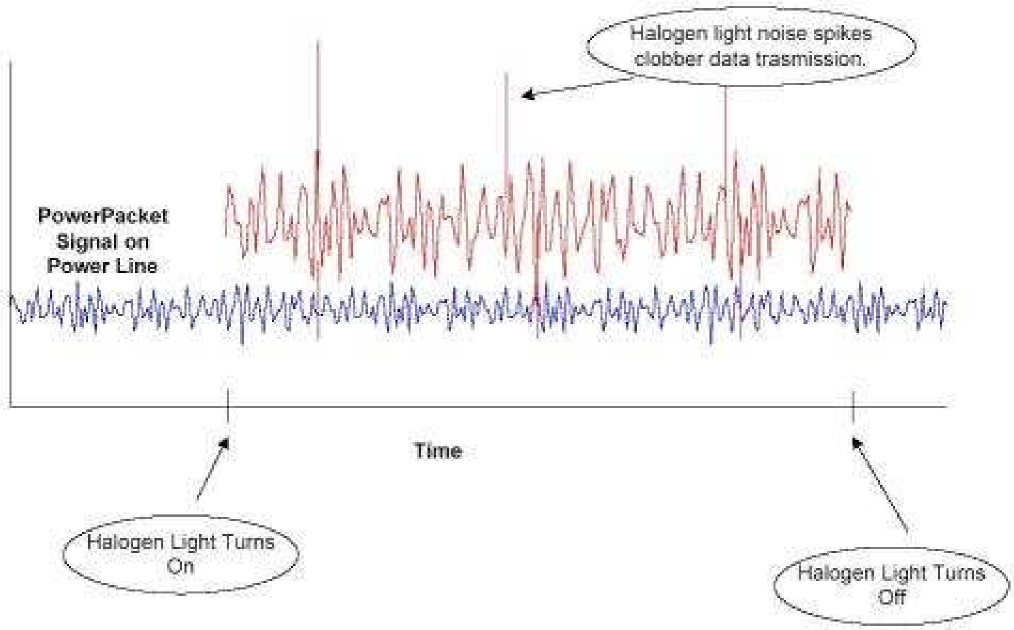
Because of the fact, that we have to modulate signals on the powerline for data-transmission issues, it's a problem that frequencies are getting weaker as they travel over the line. This behavior is called 'attenuation'. Higher frequencies are more affected by attenution than lower ones.

Bad wiring could also affect the quality of transmission.

As we don't only have our powerline-adapters attached to the power-circuit, other appliances (i.e. fan, blender, vaccum-cleaner etc.) causing 'noise' on the line which may interfere with our transmission-signals. In one moment one frequency is ideal for communication, in the other moment not. We see that this is no media with constant behavior.

To know how this could be dealt with, we will have a closer look on a implementation of Powerline by Intellon, which is called PowerPacket.

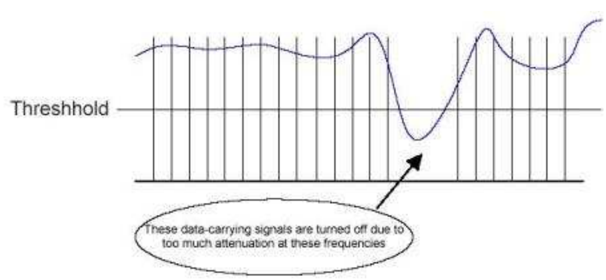
Quickly turning on appliances could cause spikes. These spikes have the ability to cause severe damage to our data stream. To avoid this data loss, PowerPacket uses Forward Error Correction. Which is also used for TV broadcasting and cellphone communication. This error correction technique sourrounds the data with "correction" bits, so that damaged data can be reconstructed. (-> Hamming-Code TI)

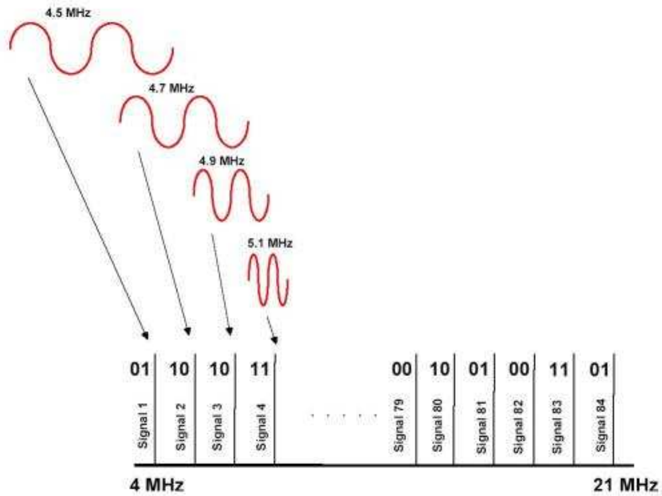


3.1 Modulation technique

PowerPacket tries to adapt to the conditons on the powerline. This technique is called Orthogonal Frequency Division Modulation. It is nearly the same modulation technique as used for ADSL (DMT). The only difference is, that we don't scale the amount of bits carried by one channel. Instead of that, the Powerline-Bridge constantly calculates a threshold. All frequencies that are lower than this mark are resonable for carrying data and will be used, the other channels will be disabled.

PowerPacket operates in the frequency band from 4.3 MHz to 20.9 MHz, which is devided into 84 channels, each channel carrying 2bit





3.2 Sniffing the line

Sniffing the line seems to be impossible, because every Powerline bridge need to have the same password, for even reply to a broadcast frame. You can set this password, using a tool, which is shipped with every node. PowerPacket also uses 56-bit data encryptionn technology. So it should be very hard to manipulate a Powerline network, even if you have some special hardware. (i.e. development kit)

But if you are aware of the network password, you should easily be able to do any sort of spoofing. (i.e. ARP-spoofing)

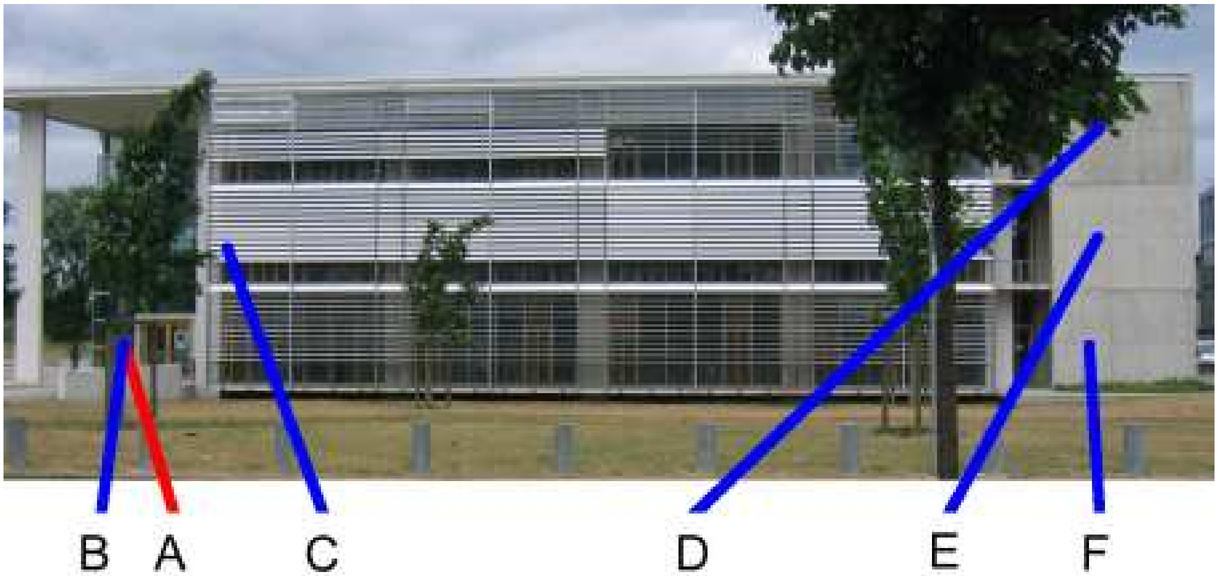
3.3 PowerPacket Specifications

	PowerPacket
throughput	~5Mbit/s
frquency band	4.3 - 20.9 MHz
range	~200m
network size	up to 12 nodes per network
price	~99Euro per for ALLNET 1682 Ethernet Bridge

3.4 Experiments

The experiments with powerline-modems has been done using powerline-bridges by Allnet. we measured the line speed with the networking benchmark-tool netperf in building 101 on the campus of the faculty of computer science:

One notebook with attached powerline modem was placed at the entrance, near the net.point (A). the other one was moved to different locations in the building to measure the throughput. So the measurements are always point A to point X.



- B:

```
TCP STREAM TEST to 192.168.1.44
Recv   Send   Send
Socket Socket Message Elapsed
Size   Size   Size    Time     Throughput
bytes  bytes  bytes   secs.    10^6bits/sec
87380  16384  16384   10.12    5.83
```

- C:

```
TCP STREAM TEST to 192.168.1.44
Recv   Send   Send
Socket Socket Message Elapsed
Size   Size   Size    Time     Throughput
bytes  bytes  bytes   secs.    10^6bits/sec
87380  16384  16384   10.19    2.40
```

- D:

```
TCP STREAM TEST to 192.168.1.44
Recv   Send   Send
Socket Socket Message Elapsed
Size   Size   Size    Time     Throughput
bytes  bytes  bytes   secs.    10^6bits/sec
87380  16384  16384   11.48    0.55
```

- E:

```
TCP STREAM TEST to 192.168.1.44
Recv   Send   Send
Socket Socket Message Elapsed
Size   Size   Size    Time    Throughput
bytes  bytes  bytes   secs.   10^6bits/sec
87380  16384  16384   10.18   3.96
```

- F:

```
TCP STREAM TEST to 192.168.1.44
Recv   Send   Send
Socket Socket Message Elapsed
Size   Size   Size    Time    Throughput
bytes  bytes  bytes   secs.   10^6bits/sec
87380  16384  16384   10.10   5.33
```

4 Outlook

4.1 DSL

There will certainly be a big market for high-speed internet-connections in the future. DSL has many advantages because it operates on the telephone line, which is mostly already there. As long as no private houshold has a fiber connection this will be the cheapest and fastest way of getting internet to your house.

4.2 Powerline

It seems to be that this Powerline bridge, as it is, has no future. There are cheaper and faster technologies available. (like xDSL or WLAN). But PowerPacket seems to be very secure and reliable for 'in-home'-use. So it may be, when it comes to home-automation, the Powerline technologie will do it's job.

5 References

Here are some articles covering the different types of xDSL and defining some commonly used expressions.

- http://www.cs.tut.fi/tlt/stuff/adsl/node1.html
- http://telecom.copper.org/xdsl-tech01.html
- http://telecom.copper.org/glossary.html
- http://www.pctechguide.com/28dcomms.htm
- http://searchnetworking.techtarget.com/sDefinition/0,,sid7_gci213915,00.html

This one is about different modulation techniques

- http://www.ciscopress.com/catalog/sample_chapter.asp?product_id={7DB87229-8DAF-419D-AF22-51516CFB38BE}&element_id={94A24926-F9A1-4C52-AEEC-E9B1DD44E7EA}

Intellon Homepage

- http://www.intellon.com

This is an interactive introduction to OFDM

- http://www.see.ed.ac.uk/~acmc/OFDMTut.html?http://oldeee.see.ed.ac.uk/~acmc/OFDMTut.html