10 km multimode fiber transmission with dispersion-resistant synthetic intensity modulation.

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ABSTRACT

A synthesized, multilevel intensity modulation technique is described for the first time. Using an unisolated 1310 nm laser diode, 556 Mbps transmission is demonstrated over 10 km of 62.5/125 multimode fiber, showing only minor dispersion effects.

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1. Introduction

Deployed fiber-optic communication systems have largely relied on digital on-off keying (OOK) to transmit information. One exception is the CATV industry's use of RF-subcarrier AM, which requires relatively tight control over device linearity. Other methods have been proposed, such as coherent communication, optical subcarrier modulation [1], digital multilevel modulation [2], optical QPSK, and others, but no one scheme has won widespread commercial acceptance for digital data transmission. For random OOK signals, the maximum frequency of interest is called the knee frequency, given by $f_{knee} = 0.5/t_{edge}$. If one assumes that a worst-case electrical rise/fall time of a gigabit-grade link is 20% of a bit time [3], then an estimate of maximum frequency of interest, as a function of bit rate R, is:

$$F_{max\,(OOK)} = 2.5R \qquad \text{Hz} \qquad \text{where R is in bits/second, without overhead}$$

This requirement places stringent demands on both the transmission medium and circuit design, and requires careful assessment of package parasitic elements for control of EMC, impedance, termination, and a host of other variables. In this paper, a new analog signaling method is described, that is compatible with directly-modulated diode lasers. Through digital synthesis of an analog signal with multiple intensity levels, digital data may be mapped into a relatively small symbol space, as in [2], returning a data transmission rate that is higher than the line transmission rate. Digital data may be encoded at greater than 2 bits/Hz, which returns more efficient use of the bandwidth-distance product of a fiber link. The use of "synthesized" signals to mitigate a dispersion limit is not new, other deliberate signals that have been employed include pre-chirped and soliton signaling. The modem and xDSL industries have been well-served by increasing data throughput without overhauling the existing cable plant.

2. Experiment

Figure 1 illustrates multilevel analog intensity modulation of a 1310 nm laser diode at frequency f_o with an even number, $n \geq 4$, peak levels. Each half-cycle sinusoid represents a data cell, of width $T_{cell} = 1/2f_o$ seconds. Symbols representing the data payload and control characters are made up of $m \geq 2$ cells, resulting in $(n/2)^m$ possible permutations per symbol. For the signal shown in Figure 1, there are $n = 10$ levels and $m = 6$ cells/symbol. Therefore there are $5^6 =$ 15,625 unique symbols in the symbol space, corresponding to 15,625 unique data codes. The number of binary bits N that may be mapped into the data symbol set can be described as:

$$2^N = (n/2)^m \qquad \Rightarrow \qquad N = m\left(\frac{\log n}{\log 2} \quad -1 \quad\right) \qquad \text{bits/symbol}$$

For the example shown, N ≈ 13.9 bits. Fractional bits, of course, cannot be mapped into the symbol space, so N is rounded down to the nearest whole number, or 13 bits. The theoretic effective bit rate, R_{eff} , may be expressed as:

$$T_{symbol} = \frac{m}{2 f_o} \quad \text{seconds/symbol} \qquad \text{and} \qquad R_{eff} = \frac{N}{T_{symbol}} = 2 f_o \left(\frac{\log n}{\log 2} \quad -1 \quad \right)$$

In this experiment, f_o = 167.0 MHz, and $R_{eff} \approx 4.64 f_o$ = 775 Mbps. In practice a portion of the symbol space is reserved for special characters, usually to represent non-data entities such as idle (carrier only), start and end delimiters, error checking and correction, and link management. Other symbols or symbol combinations may be excluded to preserve or restore average signal balance over some optimum run length. This method reduces detected baseline wander in AC-coupled receiver systems, thus simplifying receiver channel design. In the experiment reported here, an overhead of roughly 28% returned $R_{eff} \approx 3.33 f_o$ = 556 Mbps.

The experimental setup is shown in Figure 2. Symbol shapes are pre-computed in a front-end PC, and are loaded into a symbol look-up table (LUT). A truncated pseudo-random sequence, representing a data "payload," is encoded into the symbol set. This data pattern tends to excite all possible signal combinations of the transmitter, medium, and receiver link. The signal is synthesized with an arbitrary waveform generator (AWG), using a time step of 1 nsec. This test relied on use of repetitive batch-mode signaling for data transmission. A final product would map real-time data into the symbol space through high-speed hardware encoding of NRZ data. In this experiment, cell shape and symbol assignment are subject to certain constraints, among them:

- There must be an average-intensity-crossing every $1/2f_o$ seconds.
- There is one extrema between average-intensity-crossings, at one of n levels.
- 2^{nd}-order derivatives of adjacent cells have opposite signs.
- 1^{st} and 2^{nd}-order derivatives are continuous.
- Optical DC-balance is preserved over an optimum run length.

Fractional frequency Fourier analysis can be used to describe cell shape. Each cell is decomposed into a finite number, M, of weighted sinusoidal components, having frequencies above *and below* a "carrier," or center, frequency. In this experiment, M = 11, and

$$I(t) = I_{avg} \quad + \quad \sum_{j=1}^{M} a_j \sin\left(\frac{2j(2\pi f_o)}{M+1} t \quad + \quad \phi_j \right)$$

where I_{avg} is the average optical intensity, and a_j is the j^{th} weighting coefficient for a sinusoid having frequency $(2j/M+1)f_o$. A set of simultaneous equations, subject to the constraints given above, is solved to obtain coefficients a_j and ϕ_j.

The output of the AWG was AC-coupled to a 1310 nm DFB laser diode through a conventional microwave bias-T device. DC bias for the laser is provided by a constant-current source. The laser diode was connected to the test fiber through a short pigtail of single-mode fiber. The laser was in a room temperature environment, and did not have any isolator, Peltier cooler, wavelength multiplexing, external modulator, or other specialized launch or electro-optic component. The medium consisted of a number of reels of fiber according to the table below, concatenated with ST-PC connectors. An O/E converter with 1.5 GHz bandwidth, and a digital sampling oscilloscope (DSO) was used to observe the received symbols. AC-coupling and a 250 MHz lowpass filter were used with the DSO.

	MULTI-MODE	SINGLE-MODE
Fiber Type	Corning 62.5/125	Corning 9/125
Link Distance	10 km	50 km
BW×distance product	500 MHz · km	-
Launch Power	3.0 mW	2.7 mW
Received Power	7 μW	5 μW

Figure 3 illustrates a portion of the received signal after the 10 km multimode test fiber. The reader will note only a small amount of distortion and intersymbol interference (ISI) in the received signal shape, as compared to the transmitted signal of Figure 1. When attenuation is factored out, there is less than 2% deviation from the source wave form. According to the manufacturer's specification, this fiber should be suitable for OC-12 transmission to about 1 km. At a 10 km distance, this fiber link is well beyond the optical dispersion limit, and will return a closed eye pattern for OOK signaling.

Subsequently, the O/E converter was unplugged from the oscilloscope, and connected to a RF spectrum analyzer, without the 250 MHz band-limiting filter. The power spectrum included a dominant signal at f_o, the "carrier" frequency. The next strongest components were observed to be at least 40 dB (electrical) down, and were bounded by approximately $f_o/2$ to $1.5f_o$. The highest frequency, expected at $2f_o(M\text{-}1)/M$, was below the noise floor of the spectrum analyzer. From this data, we estimate the coding efficiency (in bits/second per Hertz) is over 6.3× that of OOK. The relatively narrow power spectrum supports optical signaling over a much longer distance, that is relatively distortion-free. It is worth noting, for this experiment, that signal quality is nearly the same for 50 km of non-dispersion shifted SMF, as shown in Figure 4.

3. Conclusion

We introduce a new analog modulation method that returns more efficient use of limited bandwidth of an optical communication system. An OC-12-equivalent payload is transmitted with nearly distortion-free characteristics over long fiber links, which now operate in a loss-limited, rather than dispersion-limited, regime. Moreover, the new method has an overall frequency spectrum that is a fraction of ordinary OOK. The effective bandwidth required to faithfully propagate and recover data is significantly lower than bandwidth required by OOK. In this manner, fiber link signaling distance may be vastly improved, for a relatively low data transmission rate. In an equivalent sense, a data transmission rate may be greatly increased for a relatively short length of installed optic fiber. This technique holds promise to deliver multi-Gbps upgrades to existing multimode fiber installations at low cost.

4. References

[1] L. Raddatz, I. White, M. Webster, and R. Penty, “Overcoming the modal bandwidth limitation of multimode fibre by using passband modulation,” Proc. SPIE, V2632, 1999.

[2] W. Brown, D. Hanson, and T. Hornak, “Bipolar ICs for industrial fiber optic data links,” Proc. IEEE ISSC Conference, Pg. 18, 1978.

[3] Personal communications, Dr. Howard Johnson. See also Chapter 1 in H. Johnson and M. Graham, “High Speed Digital Design: A Handbook of Black Magic,” Prentice-Hall, 1993.

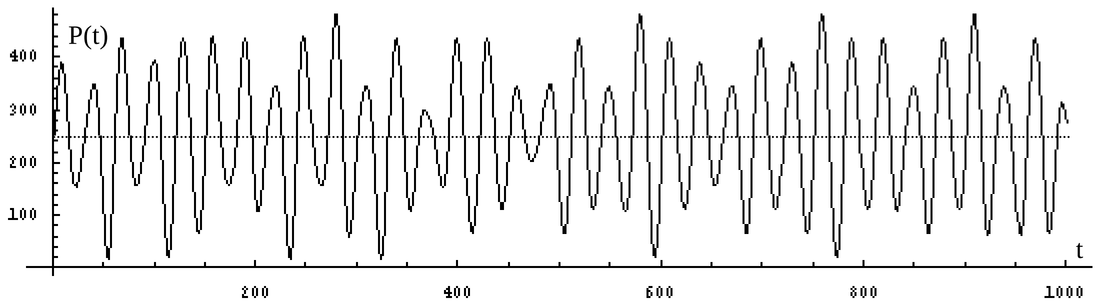


Figure 1. Output of laser diode pigtail, n = 10 levels, m = 6, P_{avg} = 3mW, 200 psec per step.

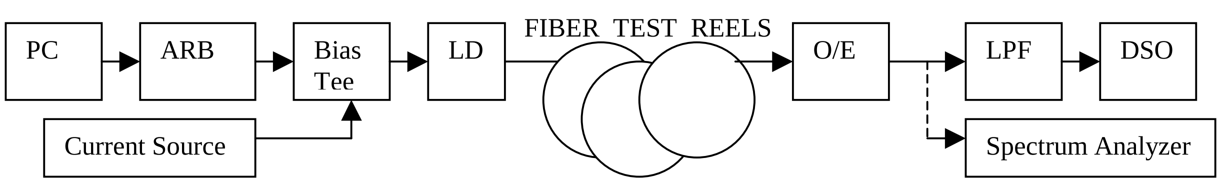


Figure 2. Experimental setup.

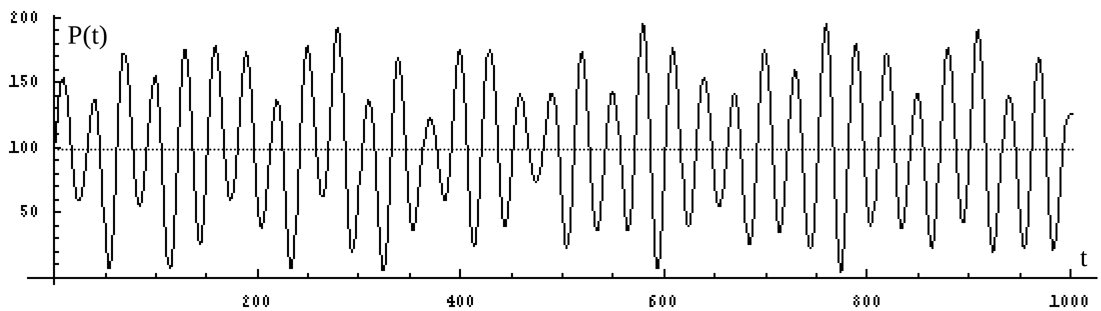


Figure 3. Received signal after 10 km of multimode fiber, P_{avg} = 7 μW, 200 psec per step.

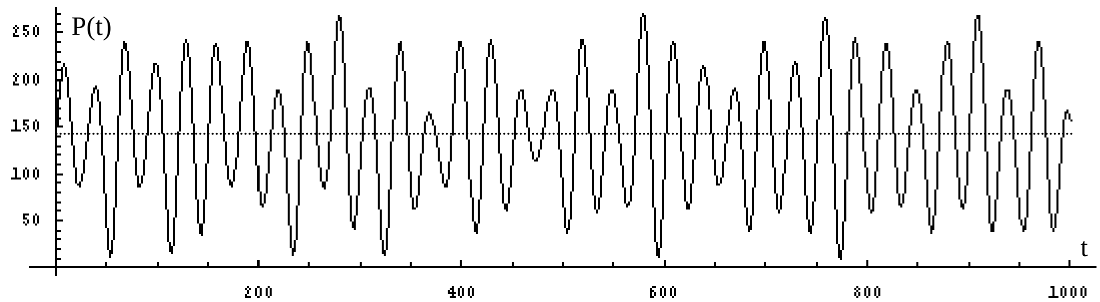
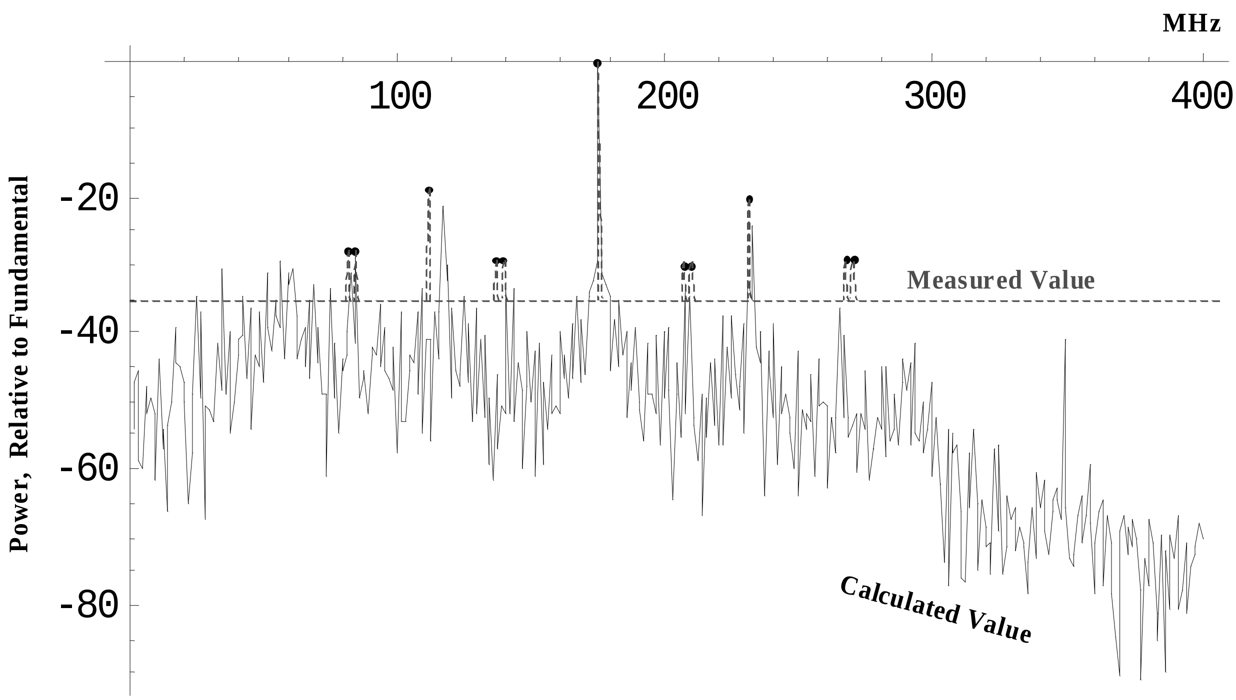


Figure 4. Received signal after 50 km of singlemode fiber, P_{avg} = 5 μW, 200 psec per step.



Annotated Figure. Computed spectrum of launched signal (solid line) and measured spectrum (dashed line) showing spectrum analyzer noise floor and 11 observed peaks (· points).

