A SEVEN POINT PARADIGM FOR THE MOTIVATION WITHIN UNGERGRADUATE RESEARCH AND LABORATORY PROJECTS

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We present seven motivational elements for learning outside the classroom and illustrate these within the context of a particular undergraduate research project. The majority of this research was actually performed after completion of the required course – motivated solely by the desire of the student to go further with the experiment and learn more about the topic. This delightful circumstance is not without precedence in our department; so we searched for (and found) what we believe are the underlying, common, key motivational elements: (1) genuine interest of the instructor; (2) good instructor-student rapport (the instructor's genuine interest should spread *naturally* to the student, without the pressures that far too often occur in graduate research); (3) a simple, but adequately accurate, theoretical model of the problem; (4) a "mystery" to be resolved; (5) some "gee-whiz" aspects in the experimental apparatus (such as magnetic levitation devices, lasers, etc.); (6) actual quality in the measurement capability of the instruments; and (7) the capability of "closing the loop" between the experiment and a simple theory.

Herein, we illustrate these seven points within the context of a specific project – one that explores many novel aspects of signal loss in optical fiber and in free-space optical links. Signal losses always increase exponentially with length in "cable," whether the cabling is coax, twisted pair, etc., or even optical fiber. In "radio" however, the losses only increase with the square of the length. So that, beyond some length, radio will always win. This "crossover" length depends on the wavelength of the source; and the transmitting and receiving antenna gains. The question then arises – how do we describe the effective "antenna gains" of an infrared LED (or laser) and an infrared detector? A simple means of relating this to the information quoted on typical data sheets is presented and tested experimentally. We also present empirical data on the length dependence of a free-space infrared link; and fiber losses in Erbium-doped-fiber. Many "mysteries" were discovered and resolved in this work; whereas other "mysteries" remain unresolved. In both cases, we note how these illustrate our seven point motivational paradigm.

Introduction

The primary educational objective of this paper is to try to understand what factors facilitate "*learning outside the classroom,*" within the context of an undergraduate research project. This project stemmed from a student's interest in a particular topic that originated as part of a required course (ECEN 420 Electrical Communication Circuits) in the Engineering Technology Department at Kansas State University. The undergraduate research was performed, without college credit, after completion of the required course, solely motivated by the desire of the student to go further with the experiment and learn more about the topic. This delightful circumstance is not without precedence in our department; so let's examine some of what we believe are the underlying, common, key motivational elements: (1) genuine interest of the instructor; (2) good instructor-student rapport (the instructor's genuine interest should spread *naturally* to the student, without the pressures that far too often occur in graduate research); (3) a simple, but adequately accurate, theoretical model of the problem; (4) a "mystery" to be resolved; (5) some "gee-whiz" aspects in the experimental apparatus (such as magnetic levitation devices, lasers, etc.); (6) actual quality in the measurement capability of the instruments; and (7) the capability of "closing the loop" between the experiment and a simple theory.

Herein, we illustrate these seven points within the context of a specific project – one that explores many novel aspects of signal loss in optical fiber and in free-space optical links. These same seven principles have also been useful in other undergraduate research projects in the Engineering Technology Department at Kansas State University. Their application to a magnetic levitation control system, for example, is a work in progress [1].

Physical Nature of this Project

One of the most compelling parts of Carlson's classic text, "Communication Systems," [2] (now in it's 4th edition) is the comparison of free-space propagation (e.g., "radio") path losses to losses incurred by "cabling." This classic issue takes on an interestingly modern twist when one considers the comparison of optical fiber losses (i.e., glass/fiber rather than copper, "cabling") to those of free-space propagation at the same wavelength. Currently, in the telecommunications industry, the preferred wavelengths [3] are around 1550nm (the minimal dispersion point of most optical fibers) which is in the infrared portion of the spectrum, at frequencies just below that of visible light. In any type of cabling (including optical fiber) the losses increase *exponentially* with distance; in "radio" (at any frequency, including optical) however, the losses only increase with the *square* of the distance. Thus, beyond some distance, radio will always "win." This seems counterintuitive: wouldn't you always do better by focusing your light into a fiber where it's confined by total-internal-reflection? The mathematics of this counterintuitive result therefore whets the students' appetite, in a modern context. Another motivating curiosity arises as follows. Since the formula for calculating radio losses naturally involves the gain of the transmitting and receiving antennas, how do we account for these at optical frequencies – when the transmitter is a laser or LED and the receiver is a photodetector (instead of a dipole or a horn or a dish or another standard radio antenna)?

A Simple Model for the Effective Antenna Gains of Optical Devices

A standard (i.e., "electrical") transmitting antenna focuses electromagnetic radiation into preferred directions (relative to an isotropic radiator) known as a radiation pattern. A receiving antenna likewise has preferred directions of receiving these waves. This is true independent of the frequency of the electromagnetic wave, thus we ought to be able to use the radiation patterns of optical devices to estimate their effective antenna gains. The details of near-field and far-field diffraction can be rather involved [4] and often these models still miss the mark (due to "re-radiation" etc.) when compared to effective antenna gain measurements [5]. Let's consider a very simple model as follows, for scaling purposes, which should hold in the far-field. The majority of power in a typical radiation pattern is roughly within an angle $\theta \cong \lambda / D$, where λ is the wavelength and D is the dimension of the antenna (typically the diameter). We can of course be more precise if we know the exact radiation pattern, but this is a good "rule of thumb" in the far-field (for example, in the diffraction of a plane wave from a square apperature, with θ defined as the location of the first field null, over 96% of the beam energy is within this angle [3]). It is important to note in passing however that this simple scaling model assumes that we are in the far-field of the antenna, i.e., that we are at a distance, z, which is far enough away from the emitting (or receiving) surface such that $z > \left(D^2\right)/\lambda$.

On the data sheets of infrared LEDs, lasers, and detectors the dimensions (*D*) of the emitting or detecting surfaces are very rarely provided. Fortunately however, these data sheets typically *do* provide emitting and detecting angles and we need only know these angles to estimate the effective gain via $G = (\pi D/\lambda)^2 \cong (\pi/\theta)^2$. Thus, we would not need to know *D* if we know θ, *provided that we are indeed in the far-field limit!* Unfortunately the definition of the far-field (defined above) does inherently involve *D* (via D^2/λ, rather than just D/λ, which would only involve θ). Therefore, we cannot know if we are in the far-field limit in the first place, from the information available on the typical infrared data sheets. This however adds to the "mystery" which serves to whet the instructor's and student's desire to resolve the issue experimentally. In our experiment we use an infrared LED (Fairchild's QED121 with a peak wavelength at 880nm) as our transmitter; and a phototransistor (Fairchild's QSD122) as our receiver. From the data sheet, our transmission angle is $\pm 9\%$, so our transmitting antenna gain (in decibels) would be $G_T = 20\log_{10}(\pi/\theta_T) = 20\log_{10}(180/9) = 26.02\,dB$. Likewise the detector's data sheet gives a reception angle of $\pm 12\%$, so our receiving antenna gain (in decibels) would be $G_R = 20\log_{10}(\pi/\theta_R) = 20\log_{10}(180/12) = 23.52\,dB$. Note in passing that these antenna gains are comparable to those of simple radio-frequency ("electrical") antenna gains, but how are we to know if we are in the far-field where this simple model would hold true? One possibility might be to look for a deviation from the $1/z^2$ dependence on the distance between transmitter and receiver that one would anticipate in the far-field.

In terms of the educational and motivational elements, notice that the above model meets the conditions of: (3) it is intuitively appealing and simple; (4) it leads to a mystery, yet to be solved; and (5) it involves modern technology. This in turn leads to the satisfaction of conditions: (1) that it is useful and innovative enough to be interesting to the instructor; and (2) that in addition to the innovative aspects, it is simple enough to capture the understanding and therefore the interest of the student. We will discuss conditions (6) and (7) in the last section, under experimental results.

Fiber versus Free-Space Losses

Path loss (or the free-space loss) of a radio link is calculated in the far-field limit to be $(4\pi z/\lambda)^2 (1/G_T)(1/G_R)$. Note the quadratic dependence of this loss on, *z*, the distance between transmitter and receiver. Thus, even if our estimations of the transmitting and receiving antenna gains, G_T and G_R, are incorrect; we should still see this dependence on *z* if we are in the far-field.

The path loss of a cable (be it "copper" e.g., coax etc., *or* optical fiber) however has an exponential dependence on *z*, which can be written as $10^{\beta z}$, where $\alpha = \beta/10$ is the number of dB of loss per kilometer, if *z* is in kilometers. In other words, the loss in an optical fiber, on a decibel scale, is αz, so that **the dB of loss doubles when you double the length of fiber.**

In contrast, the radio loss in dB is $20\log_{10}(z) - 20\log_{10}(\lambda/4\pi) - 10\log_{10}(G_T G_R)$. So that **the dB of loss only increases by 6dB, when you double the length of a radio hop**. Thus, beyond a certain distance, radio will always have less loss. For example say the loss of both is 10dB at some length. Doubling this length brings the fiber loss up to 20dB whereas the radio loss is now at 16dB. The further we go in distance, the more dramatic the effect. Consider 40 vs 16+6=32, then 80 vs 32+6=40, etc. The exponential growth of fiber loss eventually dominates the polynomial growth of free-space losses. The distance at which this happens depends of course on the loss coefficient, α, of the fiber (as well as the antenna gains). Values for α in fiber these days however are quite low, perhaps 1.7dB/km, so that even with antenna gains of 42dB, at 880nm the "crossover distance" (where radio starts to beat fiber) is almost 100km.

Nevertheless, the fact that a crossover distance exists at all seems a bit mysterious to students [motivational element (4)]; but they can see that it's true from the simplicity of the model [element (3)]; and the fact that it can be applied to cutting-edge technology [element (5)] all help to generate interest in "learning beyond the classroom." When these factors are combined with the experimental elements [(6) and (7)] we foster an environment for "experiential learning," as illustrated in the following sections.

Experimental Results

Although our main purpose here is to test the z dependence of the free-space, i.e., radio losses at infrared frequencies (in order to determine if we are in the far-field or not) we also performed a brief experiment on the losses in fiber. The educational reason for performing this part of the experiment was primarily to further incorporate motivational element (5) – the "gee-whiz" or hi-tech component of the experimental apparatus. Also, for practical reasons, we would have had difficulty in coupling our infrared LED source (running at 880nm) into our fiber apparatus (optimized for operation at 1550nm). Thus, we utilized a much more expensive, laser diode source with a "pig-tailed" fiber coupling and an optical intensity stabilizing circuit, for the fiber loss measurements (at 1550nm). This also incorporated motivational element (6) by utilizing apparatus of genuinely superior measurement capability. In addition to the increased coupling capability to fiber, and the use of a laser instead of an LED, this allowed us to not only operate at a wavelength of current interest to the telecommunications industry but also allowed us to use Erbium-doped fiber for the experiment. Erbium-doped fiber is of particular interest these days since it is utilized extensively as Erbium-doped fiber amplifiers in telecommunications networks.

By connecting three different sections of Erbium-doped fiber (each of 1 meter length) we confirmed the anticipated 1.32dB/km of loss, within 0.3 dB, (incorporating the 0.25dB of the connector insertion losses) … thus, no "mysteries" were encountered here – thereby incorporating motivational element (7) – closure between experiment and simple theory. When we looked at the free-space losses however, we found something quite different than our simple models had predicted.

Figure 1 presents the detector voltage (proportional to the incident optical power) as a function of the distance between the source and detector (on a linear scale). In this plot we clearly see the noise floor (set by ambient infrared radiation from lights in the room and dark current in the detector etc.) ensuing shortly after a distance of about 7cm.

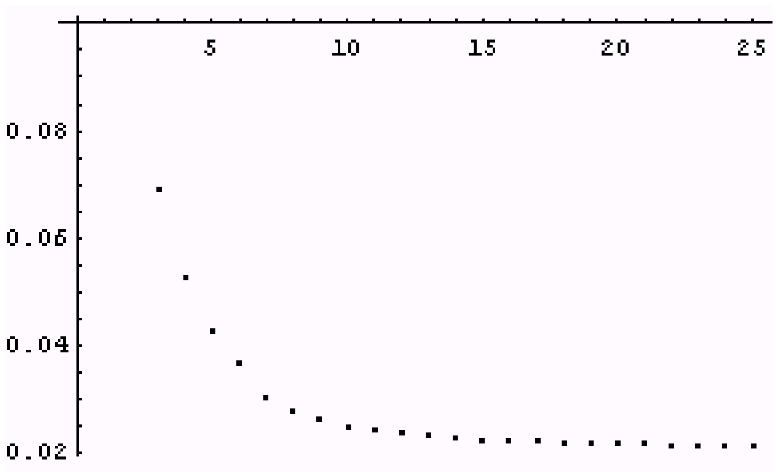

Figure 1. Detector voltage vs distance (in centimeters).

In Figure 2, we display this data on a log-log plot (i.e., dB scale) out to a distance of 1cm, (before the noise floor ensues) along with an LMS (least-mean-squares) fit to the experimental data.

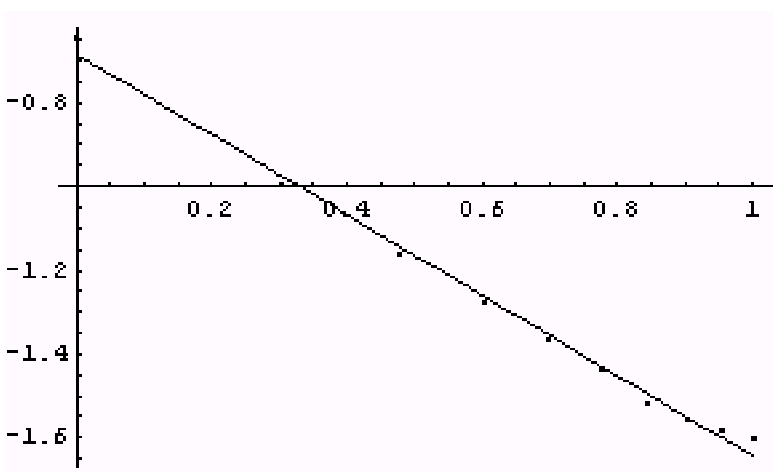

Figure 2. Detector voltage vs distance on a log-log plot

The slope of this LMS fit to a line is -.0.9, which is substantially different than the anticipated slope of –2, which should occur if we were indeed in the far-field. It should be noted that (commensurate with motivational element (6) – the use of accurate instrumentation) we made many refinements during this experiment. These refinements ranged from the elimination of "wobble" in the mechanical supports of the LED and the photodetector (via the use of vertical post mounts and an optical rail) to the elevation of each, in order to reduce the possibility of back-scattering from the environment. We also explored the use of apperatures and better detectors…all resulting in a curve fit to a line of slope much closer to –1 than the far-field prediction of –2. Currently, my new students and I are involved in further experiments in hopes of resolving this issue – our enthusiasm only further enhanced by the desire to solve "mysteries."

References

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Biography

Dr. Scott Shepard is currently an Associate Professor of Engineering Technology at Kansas State University. His research interests include: communication and control system performance issues and enabling technologies; wireless and optical systems; quantum measurement theory; encryption; distance learning and assessment issues. He worked in the telecommunications industry at Bell Labs for six years. He has a Ph.D. and a M.S. in Electrical Engineering from MIT; and a B.S. in Physics and a B.S. in Electrical Engineering from Kansas State University.