FASTER THAN LIGHT INFORMATION?

Since 1992, experimental evidence has been mounting for so called FTL (faster than light—or "superluminal") transfer of modulated signals over various media. If proven to be correct (and cost-effective), the implications for the communications industry are *staggering*. Although substantive peer reviewed data has been accepted by the physics community (and repeated in many laboratory experiments [1],[2])—the FTL hypothesis remains a controversial (and as yet, unproven) explanation. Analysis of experimental FTL findings varies greatly amongst physicists. "Tunneling is the one and only observed violation of special relativity [3]" according to German physicist Günter Nimtz (who coauthored the first modern superluminal study, and has been able to replicate this phenomenon across a variety of media and bandwidths). He, and other proponents of the FTL hypothesis point out that while special relativity is *challenged* by these experiments, the quantum processes they discuss are not part of the purview of special relativity which concerns classical mechanics—so no laws are being re-written. This report will outline 3 main aspects of the superluminal "story":

1. **Experimental Evidence for FTL signal transfer.**
2. **FTL Theory and Critiques of FTL Theory, with a primer in "quantum tunneling" (the physics that appears to be central to FTL phenomena).**
3. **Applications (Present, Near-Term, and Long-Term).**

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1. Experimental Evidence for FTL signal transfer

1.1 Summary of: "On Superluminal Barrier Traversal", Enders and Nimtz, 1992 [4]:

Enders and Nimtz begin their paper with a discussion of their rationale for choosing an undersized waveguide to conduct their experiment. A waveguide is a structure to restrict wave energy to 1 direction—minimizing amplitude or energy loss (without a guide, a wave would propagate in all directions, and dissipate much more quickly). The authors were looking for a rectangular waveguide that would satisfy an "imaginary" variant solution to the wave equation defined by Helmholtz:

$$k^2 = \left(\frac{2\pi}{\lambda_{vac}}\right)^2 - \left(\frac{2\pi}{2b}\right)^2 [4]$$

If the vacuum wavelength is greater than 2b (the width dimension of the waveguide) at the corresponding frequency of the wavelength, k (the wave number) becomes imaginary and the wave loses its quality of time. When that condition occurs (called a boundary condition), the part of the wave within the boundary or barrier becomes imaginary, or time-invariant—*regardless* of the size of the barrier. They outline a procedure to create this boundary condition (> than 2b) by using an undersized waveguide [4].

Their apparatus was fairly straightforward, and accomplished their aim to create a waveguide (2b) smaller than the vacuum wavelength:

> Rectangular waveguides (X-band and Ku-band) were used, their cross-sections being IO.16x 22. 86 mm/ and 7.90 x 15.80 mm~, respectively. The cut-off frequencies are 6.56 GHz for the larger and 9.49 GHz for the smaller waveguide, the latter being used as the barrier below cutoff [4].

These are very high frequency guides (The X Band is in the 8.0 to 12.0 GHz range; the Ku band is in the 12-18 GHz range).

The authors assert that their measurement of phase accuracy should- be within 1 degree. They discuss the pulses that they sent through the waveguide array, which used amplitude transformations to minimize "head and tail" of the pulse—providing a more accurate time measurement at both ends. Using 4 different waveguide lengths, the traversal of the pulses from one side of the barrier to the other was virtually identical (under normal conditions—larger waveguides should take longer to traverse). They arrive at the conclusion that the "barrier traversal velocity" (that is: the speed through the "barrier" created by the boundary condition outlined in their introduction) must be "above the vacuum velocity of light [4]."

1. Experimental Evidence for FTL signal transfer

1.2: Summary of *Subluminal to superluminal pulse propagation through one-dimensional photonic crystals with a three level atomic defect layer,* M. Sahrai, S. Aas2, and M. Mahmoudi, 2004 [5]:

In their 2004 paper: M. Sahrai, S. Aas2, and M. Mahmoudi are concerned with superluminal signal velocities of light in a medium. In describing the background of their apparatus they state:

> It is shown that coherent control of the optical properties of a dispersive medium leads to new phenomena [5].

This concept of "coherent control" relates to their choice of medium, and the "doping" or, impurities introduced to that medium to achieve a quantum tunnelling effect. A one dimensional photonic crystal is a structure that permits only allowable wavelengths of an incident electromagnetic wave to pass through it. The allowed wavelengths are called modes, and the disallowed wavelengths are called band gaps. A 1 D photonic crystal allows the permitted wavelength to move in one dimension only. They describe their apparatus as follows:

The optical thickness of each layer is nAdA =*nBdB* = λ0/4 , where λ0 = 692 nm is the midgap wavelength. The thickness of the defect layer is *nDdD* = λ0/2, where *nD* = *nB*. The midgap frequency is *ω*0 = 2*πc*/λ0, where *c* is the speed of light in vacuum [5].

Here the authors are relating the dispersive medium's dimensions to the frequency of the incident wave and to the speed of light in a vacuum in a similar way to Nimtz's undersized waveguide in the microwave experiment. They write:

> We show that the width of the defect layer doped with three-level atoms can substantially change the group velocity of the transmitted pulse inside the 1DPCs. It is clear that at any spatial position, the temporal profiles of the both electric field|φ1(z, t)| and magnetic field |φ2(z, t)| are approximately Gaussian curves [5].

The encoded Gaussian curves were preserved (at least approximately)—meaning that despite the increase in group velocity, "information" (wave-shape) *was* preserved.

The width of the doped layer changes the velocity of the transmitted pulse, because the width of the doped layer can induce a quantum tunnelling boundary.

Most of the study presents findings of transluminal speeds in both electrical and magnetic readings at the optimal layer widths. As in other similar studies, the authors are measuring distance between peak frequencies. They write:

> For a small frequency detuning,the slope of dispersion is negative that lies between two resonant transmission peaks This is to say that the group velocity of the light pulse is exceeding the speed of light pulse in vacuum [5].

-An exciting set of findings, the results of this paper further support the theory that FTL signal transmission *is* possible.

1. Experimental Evidence for FTL signal transfer

1.3: Summary of *Electronic data transmission at three times the speed of light and data rates of 2000 bits per second over long distances in buffer amplifier chains,* Kühn, 2019 [6]:

Steffen Kühn observes a similar phenomenon with a very different approach, medium, and experimental set up. He begins his study with the observation that almost no data communication currently occurs in what he calls the "base band" (a band near 0 frequency, not suitable for reliable communication and subject to noise and signal loss). He discusses the early study of analog telegraph signals in a sub-branch of electrical engineering called: "transmission line theory [6]." And he notes that equations used in this theory: the "telegrapher's equations", don't adequately model wave propagation when the ULF wavelength exceeds the length of the media used (ULF wavelengths can be 100 – 1000 km). He then outlines his effort to study ULF speed in shorter wires. His apparatus included:

- 1 PicoScope with AWG (arbitrary waveform generator),
- BNC connection cables and connectors,
- 1 Linux PC
- Several hundred meters of coaxial cable (RG6 PVC, 135 dB, characteristic impedance: 75 Ohm, 0.12 =m, 50 pF=m) [6]

The first phase of Kühn's experiment involved comparing the response time of a long length of coaxial cable to a short length of coaxial cable both extending from a single generated output sinewave of the PicoScope, to two inputs of the PicoScope. The resulting waves were sent to a PC running an open-source analysis program that could compare the delay between the two signals. He generated sine waves of:

> 1000, 1252, 1568, 1964, 2460, 3080, 3857, 4831, 6050, 7576, 9488, 11882, 14880, 18634, 23336, 29224, 36598, 45833, and 57397 Hz and cable lengths of 500, 300, 200,and 100 meters [6].

He switched outputs, inputs, and wave frequency in order to control for device-based measurement errors. The data indicated that for frequencies between 30 – and 15,000 Hz, phase velocities were well above c (or the speed of light). Above 15,000 Hz, velocities fell below c [6].

In the second phase of the experiment, he connected 2 100 m coaxial cables, joined by a buffer amplifier to boost the signal's strength. He found similar superluminal speeds and good signal strengths over the longer (amplified) medium. Using recorded data, he plotted phase velocity against wave frequency, and found a predictably downward sloping curve—meaning that higher frequencies equated to slower phase velocities. Using software analysis, he was able to distinguish wave "packets" at 5 ms intervals—which could equate to a data transfer rate of 2Kb/s [6].

Kühn summarizes his findings that FTL information transfer is possible in small packets using ULF signals and employing buffer amplifiers at regular intervals to improve signal integrity. He recommends more research and initiative in the possibilities of ULF transmission [6].

2. FTL Theory: Background, Arguments and Counterarguments:

2.1. A Brief History and Precis of Quantum Tunneling:

Quantum tunneling can be described as the possibility of a particle to exist in a so-called: "forbidden state" of classical mechanics. At tiny scales, the laws of classical mechanics break down, and particles obey *probable* locations instead of deterministic ones. This means that in a small but definable percentage of instances, they can "jump" across a barrier, even without the energy or momentum required to do so by classical mechanics. This jumping occurs without work being done (in classical mechanics, work W= F(force)*s (displacement)). The "forbidden" quantum particle doesn't have a "speed", the process is time invariant. It can reassemble itself on the other side of the barrier with minimal change and no time delay.

Quantum tunnelling was first observed by Friedrich Hund investigating the behavior of gasses in 1927. In 1928 it was used to describe radioactive decay. In 1973 Leo Esaki, Ivar Giaever and Brian Josephson won the Nobel Prize in Physics for their prediction of quantum tunnelling in superconductors. It has current applications in a number of areas: electron microscopy, tunnel diodes (which have a negative resistance due to tunnelling), and quantum computing.

In his 2004 paper: "Superluminal Signal Velocity and Causality" Gunter Nimtz writes:

> Several quantum mechanical studies on tunneling came to the conclusion that tunneling a barrier proceeds in zero time. A short time is spent at the barrier front boundary. This result is in agreement with the photonic tunneling experiments: zero-time is spent inside a barrier [7].

This "zero-time" process may be key to FTL wave propagation. Nothing is exceeding the speed of light, instead, a process that doesn't involve speed in the classical sense at all is occurring at the quantum level.

Quantum tunnelling has a connection with the Schrodinger wave equation. The wave equation quantifies the probability of a particle's position *s* at time *t*. It consists of a real and imaginary component. Some of its solutions allow for tunneling to occur in barriers of particular energies. In other words, quantum tunneling is a particular solution set for the Schrodinger wave equation. Nimtz writes:

> The model used for defining the signal velocity is based on a refractive index n(ω) with a finite real part. The tunneling process, however, has a purely imaginary refractive index, which results in zero barrier traversing time and thus in an infinite velocity inside barriers [7].

2 FTL Theory: Background, Arguments and Counterarguments:

2.2 Critiques of FTL Theory:

There have been many published critiques of FTL theory. Most begin with the basic disagreement between the special theory of relativity (STR)--which has yet to be disproven in any widely recognized experiment--and the evidence for FTL signal transmission. Not only are wavelengths faster than light *not* allowed by STR, information *cannot* travel faster than light in STR either. Popular criticisms of the FTL theory tend to remap the results of the experiments along conceptual lines that better support STR.

In his book *Special Relativity and Motions Faster Than Light* Moses Fayngold writes:

> Because all observable properties of material objects are real, the appearance of the imaginary values in the theory [FTL] indicates that corresponding quantities cannot be measured. But what cannot, in principle, be observed does not exist. In other words there cannot be any superluminal particles w.

In "TUNNELING TIMES AND SUPERLUMINALITY", Raymond Chiao *et al* [9] describe superluminal propagation as: a superluminal transformation of the center of mass of a wavefront *not* the entire wave. In addition to disproving the FTL hypothesis, these findings would also cast doubt on the ability of the phenomenon to carry any information as any signal integrity is lost in the wave transformation process.

In his paper: *Do single photons tunnel faster than light?* Herbert G. Winful (who has specialized in quantum electrodynamics) makes some of the most widely quoted arguments against FTL. He states:

> It is universally assumed that the group delay in tunneling is a transit time of a wave packet from input to output. We have critically examined this assumption and have shown that the group delay is not a transit time but the lifetime of stored energy (or stored probability) escaping through both ends of the barrier [10].

In other words, Winful views the FTL hypothesis as a simplification of the full wave equation. In his more rigorous treatment, stored energy is at play. He calls the "boundary" defined by quantum tunnelling a "cavity [10]", in which the incident wave reverts to a standing wave (of no period), and the potential energy of the input wave is channelled to an output wave with the same characteristics as the input. Winful is suggesting the tunnelling is really a behavior of a longer, irregular wave which builds up energy in a standing wave junction he calls the "cavity." Descriptions of cavity phenomena are established in physics literature. No imaginary wave is needed--and no violation of STR is implied [10].

2 FTL Theory: Background, Arguments and Counterarguments:

Counterarguments against the Critics of FTL:

A central counterargument against the charge that FTL violates STR emphasises the fact that quantum processes involved in tunneling are outside of the purview of STR. The traversal of a particle across a quantum boundary doesn't have a velocity component—so saying it violates a velocity limit (c) doesn't necessarily overlap with STR. On either side of the boundary, the wave travels at c. More specifically, FTL proponents have said FTL *challenges* STR—but it doesn't violate any of its laws.

Nimtz makes some interesting claims about so-called "causality violation" in FTL (the implication that if information can travel faster than light, the future can affect the past). In *Superluminal Signal Velocity and Causality* he writes:

> In spite of an increasing superluminal signal velocity vs $\rightarrow \infty$ the general causality can not be violated because the signal time duration increases analogously _t $\rightarrow\infty$ [7].

Nimtz goes on to say that the duration of the tunneling waves is finite, and their conditions require preservation of the imaginary component of the waveform (otherwise, the imaginary and real components will recombine and all information will be lost). So you cannot accelerate a waveform infinitely according to Nimtz—the signal time increases at a rate analogous to the velocity. He also points out that the waves themselves never exceed c—they simply traverse a barrier due to the quantum tunnelling effect instantaneously, altering their total travel time to exceed c.

Nimtz agrees that Winful's cavity approach is well reasoned and well defined. But, he argues, the data doesn't hold to the expected values if a cavity standing wave is at play. He writes:

> […] the measured tunneling time is by about one order of magnitude shorter than the time to build a standing wave in a cavity [7].

In addition, the calculated traversal times are shorter than the predictions of the cavity approach. In other words, the experimental evidence disagrees with Winful's hypothesis (however well-argued).

Similar data-based arguments are made against Raymond Chiao's claim that the center of mass is undergoing a superluminal transform—but the wave itself isn't exceeding c. Nimtz writes:

> […] the measured single photon coincidence profile is exactly the same for the tunneled as well as for the vacuum traveled photons [7].

If the profile is the same, Nimtz reasons, then there can't be a transform to the center of mass which would imply a forward sloped profile on exiting the barrier.

3. Applications of FTL and Quantum Tunneling:

3.1. Present:

The Scanning Tunneling Microscope (STM) is in wide use today. Its inventors (Gerd Binnig and Heinrich Rohrer) won the Nobel Prize for their work in 1986. The STM introduces a bias voltage between the tip of the microscope and the surface to be examined which allows a boundary condition for electron tunnelling. This allows for very high resolution images of surfaces.

The tunnel diode is another widely used device employing quantum tunneling. Tunnel diodes leverage properties of quantum mechanics to conform to a negative resistance. The first of these diodes were invented by: Leo Esaki, Yuriko Kurose, and Takashi Suzuki in 1957, working for a predecessor of Sony Corporation in Japan. They are usually made with germanium, and all have a heavily doped P/N junction (in other words, a P/N junction with above average impurities introduced). They are unique in their ability to operate at high microwave band frequencies.

Quantum computing uses quantum states to store and transfer information in units called qbits much more efficiently than traditional silicon computers, and with an added state that allows users to attack different types of problems. Although commercial applications are some distance in the future, Quantum computers have already solved problems considered unsolvable (in reasonable time) by traditional supercomputers. Because quantum computing operates at quantum scales, the effects of tunnelling are an important part of a quantum computer's operation.

3. Applications of FTL and Quantum Tunneling:

3.1. Short Term:

Signal speed: Physicist Alain Hache (University of Moncton) suggests the techniques of FTL may boost signal speeds in excess of 50%. Electrical signals currently travel at about 1/3 c in wire. Hache suggests they may very likely approach c with this technique in the realizable future [11].

Nanoelectronics Design: Quantum tunnelling is a "fundamental physical principle [12]" when designing single or small group electron arrays that form qbits. This area of research grows daily. And new advances in modelling create more stable quantum computers.

3. Applications of FTL and Quantum Tunneling:

3.2. Long Term:

If the evidence that supports FTL signal transmission is proved correct, new technologies will revolutionize the communications industry. Vastly increased transmission speeds will have an immediate effect on the way stock markets (and other real-time-critical institutions) function. It may allow for more accurate experimental data reliant on transmission speeds. And significantly reduced latency in all network applications will mean new software and hardware to leverage these benefits. Coupled with improvements in quantum computing and parallel quantum computing—we will be able to solve previously insurmountable problem sets in realizable timeframes. Some of these might include climate simulations, biochemical simulations for medicine and chemistry research, cryptography and cryptocurrencies, and non-invasive resource exploration.

Conclusions:

1.1. Enders and Nimtz' 1992 microwave study proved that superluminal microwave signal velocities can be recorded with high accuracy (as they are defined in the study). Although its wider conclusions remain controversial, this paper continues to be cited—and its findings have been replicated.

1.2. M. Sahrai, S. Aas, and M. Mahmoudi were able to record superluminal velocities of light in a tightly controlled dispersion medium. Their findings show that the pulses retained their Gaussian shape, and that a direct relationship between the width of the dispersion medium and the group velocity of the pulses exists—further suggesting that a quantum tunneling condition was met at certain widths.

1.3. Steffen Kühn took a very different approach to achieve similar superluminal results. Using ULF signals in an undersized (shorter than ULF wavelength) wire, he was able to transmit FTL information which he analyzed digitally. He then extended his experiment to include cables joined by signal buffers—and found that signal quality could be preserved over longer distances at 2Kb/s. Kühn's research suggests that FTL transmission may not be restricted to short distance laboratory experiments.

2. FTL phenomenon remains controversial. While experimental evidence supporting the quantum tunneling hypothesis continues to grow, many physicists feel that the measured quantities support a different subset of the wave equation solutions—or that there are inherent paradoxes in the FTL interpretation which are better resolved by STR. As practical uses for quantum tunnelling emerge, and better approximations of these results are posited, the theoretical arguments for or against FTL may subside in favour of concrete, usable applications and technologies.

3. Since the middle of the last century, quantum tunnelling applications have been important to electronics, chemistry, and microscopy. Two Nobel prizes have been awarded for contributions to physics involving quantum tunnelling. The possibility of faster (but still subluminal) information transfer leveraging quantum tunnelling is a very real frontier in the communications industry. In the longer term, superluminal information transfer could radically improve our ability to model and interact with our world. If superluminal transfer speeds are achieved reliably over long distances, communications networks, protocols, and component devices will have vastly expanded possibilities.

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