Neutrino Communication
Using neutrinos for communication between New York and Tokyo

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July 22, 2022

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Motivation

- The importance of communication: desire of humans for communications over a distance greater than that feasible with the human voice.
- Limitation of current communications: environments where electromagnetism waves are damped and do not penetrate easily
- Neutrino's ability to penetrate matter

Contents

Comparison to conventional communications*,**,†

Medium	Propagating matter and space	Applications
Microwave (Radio wave)	Line-of-sight paths	Point-to-point communication systems, satellite communication, deep space radio communications
Visible, IR lights	Air, space	Free-space optical communication
Mid IR	Optical fiber	Fiber-optic communication
Acoustic waves	Air, water, etc	Underwater acoustic communication
HF electrical signals	Coaxial cable, etc	Cable transmission
Neutrino	**Almost anything and everything**	Point-to-point global communication, communication with submarines, interstellar communication, planetary exploration

*Seybold et. al., Introduction to RF Propagation, pp. 55–58.

**Understanding Wavelengths In Fiber Optics, 2019.

†I. F. Akyildiz et. al., Ad Hoc Networks, 3 (2005).

Contents

Is it possible?

- Weak interactions: an advantage, but also implies challenges for beam intensity and detector
- 2012: Low-rate communications over a distance of 1.035 km using the NuMI beam line and the MINERvA detector at Fermilab.
- From New York to Tokyo: 9600 km through the Earth $\longrightarrow$ attenuation??

Attenuation in propagation through Earth

The number of particles left N after traveling a distance x can be expressed as:

$$N = N_0 \exp(-\sigma \rho x) \tag{1}$$

where N_0 is the initial number of particles, $\sigma\,(cm^2)$ is the interaction cross section and $\rho\,(g/cm^3)$ is the density of matter which the particles pass through.

- For neutrino, $\sigma/E \approx 10^{-38}\,cm^2/GeV$
- Take the standard density of rock $\rho \approx 2.65\,g/cm^3$
- x $\approx$ 9600 km (from New York to Tokyo)

$\longrightarrow$ We have $N \approx N_0$, the reduction is very small

Attenuation in propagation through Earth (cont.)

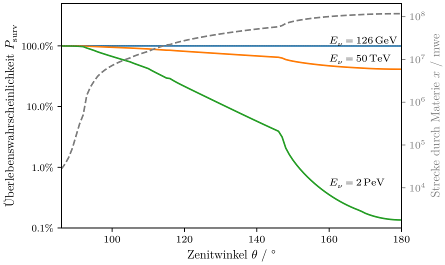

Figure 1: The neutrino attenuation

Neutrino survival probability:
$P_{surv} = \exp(-N_A \times \sigma(E_\nu) \times X)$
N_A is the Avogadro constant, $\sigma(E_\nu)$ is the total neutrino cross section at energy E_ν and X is the slant depth in meters water equivalent.

The x-axis is the zenith angle. The left y-axis shows the survival probability of a neutrino, and the right y-axis shows the slant depth in meters of water equivalent that the neutrino at that zenith angle would be passing through.

- 9600 km of rock, density 2.65 g/cm^3 corresponds to 26000 km of water equivalent.
- According to this plot: zenith angle 110 degree.
- For a 120 GeV beam, almost no neutrino attenuation.

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Proton beam, detector and NuMI experiment

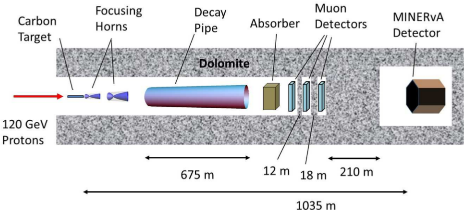


Figure 2: Layout of the NuMI beam line used as the neutrino source and the MINERvA detector*

- 88% muon neutrinos
- 11% muon antineutrinos
- 1% electron neutrinos
- The energy spectrum peaks at 3.2 GeV with FWHM about 2.8 GeV

*D. Stancil et. al., Mod. Phys. Lett. A 27 (2012)

- Using NuMI beamline - world class source.
- A series of accelerators produces 8.1 μs pulses of 120 GeV protons every 2.2 s.
- Proton beam scatter with carbon target produce many pions, kaons, and other particles.
- Pions and kaons then decay into neutrino in a decay pipe.

Proton beam, detector and NuMI experiment (cont.)

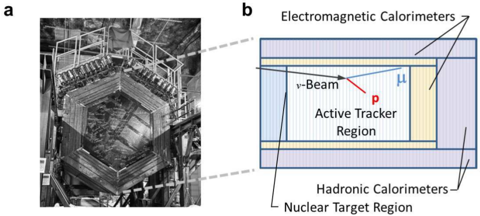
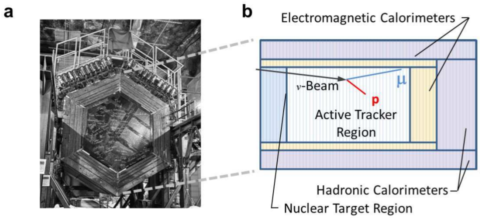


Figure 3: The MINERvA detector. (a) Photograph. (b) Cross sectional diagram of the detector*

- The MINERvA detector is located in a cavern about 100 m underground.
- The basic element of the detector is a hexagonal plane assembled from parallel triangular scintillating strips. The full detector has 200 such planes, and a total weight of 170 tons.

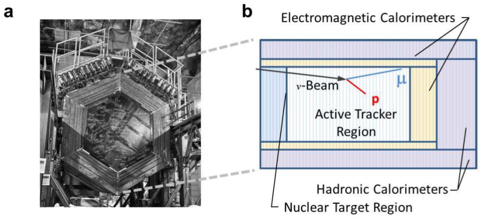
*D. Stancil et. al., Mod. Phys. Lett. A 27 (2012)

Proton beam, detector and NuMI experiment (cont.)



- The central tracker is surrounded by calorimeters that have alternating layers of metal and scintillator used to contain high energy showering particles and measure their energy.
- The detector was designed to collect more than 16 million neutrino events over four years of beam time.

Proton beam, detector and NuMI experiment (cont.)



- A charged particle passing through a scintillator produces scintillation light proportional to its deposited energy.
- When the light passes through wavelength shifting fibers embedded in the scintillator, fluorescent dopants in the fibers emit light at a new (green) wavelength, much of which is then transmitted through the optical fibers.

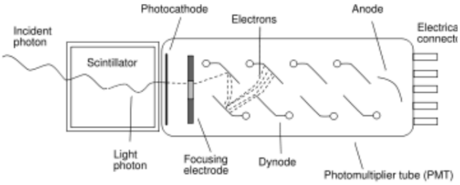


Figure 4: Photomultiplier tubes*

- Optical cables transport that light to photomultiplier tubes located above the detector.
- These signals are used to determine the deposited energy of the particle and the position of the particle.

*Tracking/Calorimeter Neutrino Detectors, Prof. Jennifer Thomas's lecture

Proton beam, detector and NuMI experiment (cont.)

- The signal for this measurement is charged-current neutrino interactions that contain muons in the final state.
- The range of these muons is typically many meters in the plastic scintillator, so that each muon leaves a signal in at least several tens of scintillator strips, and such events are distinguished by their long and straight trajectories.
- At the reduced intensity of 2.25×10^{13} protons per pulse used in this study* of neutrino communication, an average of 0.81 events is registered during each pulse.
- With a time resolution of a few nanoseconds for the muons selected for this demonstration of principle, it is possible to disentangle multiple events in the 8.1 μs beam bursts.

*The NuMI Facility Technical Design Report, Fermilab, 1998

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How to encode information using neutrino beam?†

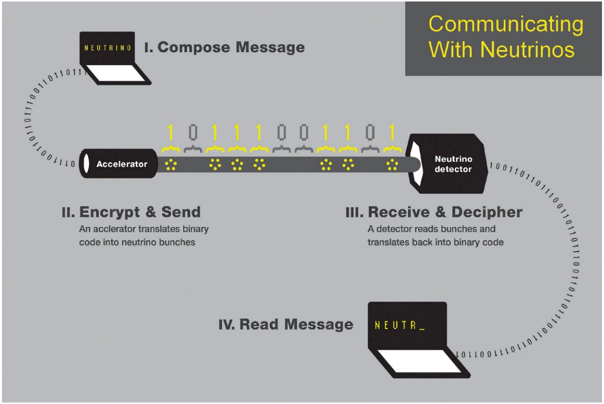


Figure 5: Communication with neutrinos*

- Using the neutrino beam is on-off keying (OOK)
- A "1" or a "0" is represented by the presence or absence of a beam pulse, respectively
- In the NuMI beam line, OOK was implemented by controlling proton beam pulses from the Main Injector
- A "1" bit corresponds to a beam pulse with an observed event, and a "0" bit is no events

*https://phys.org/news/2012-03-wireless-message-neutrinos.html

†D. Stancil et. al., Mod. Phys. Lett. A 27 (2012)

Poisson process in neutrino communication[†]

Poisson distribution[*]

$$P(X = k) = \frac{\lambda^k e^{-\lambda}}{k!} \qquad (2)$$

where

- k is the number of occurrences
- e is Euler's number
- ! is the factorial function

(discrete probability distribution, use for radioactive decay process)

- The occurrence of events is modeled as a random Poisson process
- λ is the expected number of events per pulse when the beam is "on"
- The probability that no events are observed during a pulse is $e^{-\lambda}$,
- The bit-error rate (BER) is $e^{-\lambda}/2$, assuming that 1 and 0 are equally

[*] https://en.wikipedia.org/wiki/Poisson_distribution

[†] D. Stancil et. al., Mod. Phys. Lett. A 27 (2012)

The structure of compose message*

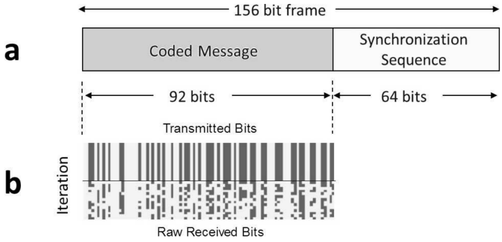


Figure 6: Format and representations of transmitted data

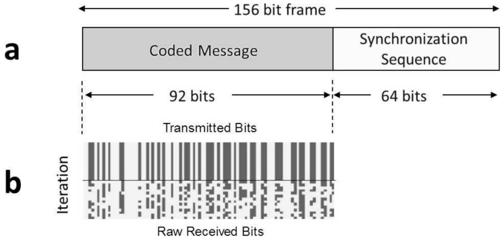
For example, let's compose the "neutrino" word. 8 character word is expressed in 5-bit of ASCII.

Character → Decimal → Binary

- n → 110 → 01101110
- e → 101 → 01100101
- u → 117 → 01110101
- t → 116 → 01110100
- r → 114 → 01110010
- i → 105 → 01101001
- n → 110 → 01101110
- o → 111 → 01101111

*D. Stancil et. al., Mod. Phys. Lett. A 27 (2012)

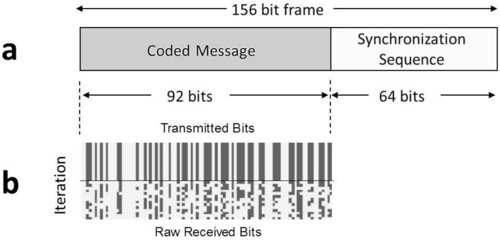
The structure of compose message (cont.)



Total 156 bits frame:

- 92 bits for encoded message
- 64 bits pseudo-noise (PN) synchronization sequence
- This frame is repeated for the duration of the experiment. The accelerator was operated at 25 pulses spaced by 2.2 s, interval 6.267 s

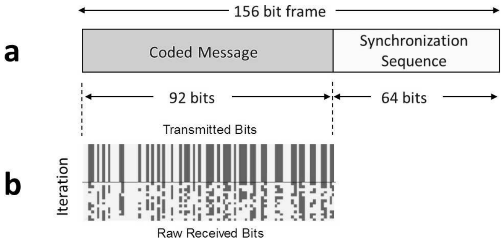
How to decode message?*



- Decoding the message requires the locations of the frames within the data
- This is done by searching for the 64-bit pseudo-noise sequence as a "sync" word that signals the end of each frame
- Search for 2 sync words spaced exactly by 156 counts to ensure symbol synchronization throughout the frame

*D. Stancil et. al., Mod. Phys. Lett. A 27 (2012)

Estimated the channel*



- 15 synchronized frames are used to recover the message and to estimate of the channel
- Each row of pixels representing the transmitted data, dark pixels represent "1" and light pixels are "0"
- 78% are received correctly
- Errors can be reduced by combining multiple frames.
- The transmitted message is recovered perfectly if the results of all the frames are "1"

*D. Stancil et. al., Mod. Phys. Lett. A 27 (2012)

Estimated bit-error rates (BER)*

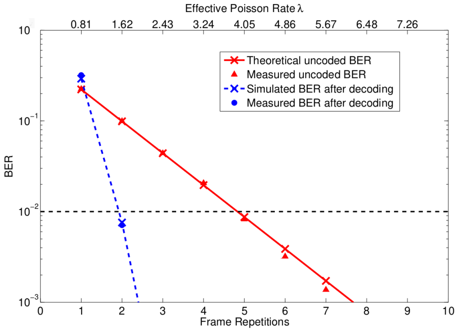


Figure 7: A comparison of predicted and measured bit-error rates

- Theoretical prediction of BER $= e^{-\lambda}/2$ with $\lambda = 2 \times 1402/3454 = 0.81$ (a half of bit is 0, 1402 events observed in 3454 counts)
- It should be noted that 99% of the transmitted bits are decoded correctly using only 5 frames
- After error-control decoding, the value is very good agreement with the simulated Poisson after only 2 frames

*D. Stancil et. al., Mod. Phys. Lett. A 27 (2012)

The capacity

The theoretical capacity of the channel with OOK is given by*

$$C/B = \log_2 \left[1 + [1 - \exp(-\lambda)] \times \exp\left(\frac{-\lambda}{\exp(\lambda) - 1}\right)\right] (bits/pulse) \quad (3)$$

with B is the baud rate (pulses/sec), C is the channel capacity (bits/sec), and $\lambda = 0.81$ is the average number of events per pulse in experiment.

- Theoretical capacity of C/B = 0.37 bits/pulse
- Experimental of C/B ≈ 0.22 bits/pulse ≈ 0.1 bits/sec (taking the error probability is 1%)

*D. Stancil et. al., Mod. Phys. Lett. A 27 (2012)

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Summary

- The experiment using the NuMI beam line and the MINERvA detector achieved a data rate of about 0.1 bits/sec
- At that rate, it would take more than 6 minutes to accurately relay the simple message "neutrino"
- It would take about 15 billion years to transfer the entire 5.8 petabytes of data stored at the nonprofit Internet Archive, which is just a little longer than the age of the universe
- As a result, even with a world-class proton accelerator and a massive particle detector, neutrino-based communication is inefficient

Conclusions

- Long-distance communication using neutrinos from Tokyo to New York about 9600 km is impossible
- Detectors optimization for detecting interactions in a larger mass of target material than is visible to MINERvA, as well as beams that are more intense and with higher energy neutrinos than NuMI
  (the beam narrows and the neutrino interaction rate increases with neutrino energy)
- The largest detectors, such as IceCube, which uses the Antarctic icepack to detect events, are of particular interest

Don't worry, be happy and look to the future!

Thank you for your attention!