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Design and Simulation of a Low-Cost Optical Fi-bre Fault Localisation Circuit Using Time-Domain Reflectometry Principles in NI Multisim

An Electrical-Analogue Approach to Emulating OTDR-Based Fault Detection in Optical Fibre Links

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Abstract
Fault detection and localisation in optical fibre communication links is usually done with an Optical Time Domain Reflectometer OTDR. But it is in practice, kind of accurate, yet it can be pricey and not that easy to access when you want something for training or just fast preliminary checks. Here we talk about the design, simulation, and analysis of a low cost electrical analogue circuit, and kind of keep it similar in spirit to what OTDR does. The main goal is to mimic the fault-localisation behaviour of an OTDR, by leaning on ordinary transmission-line plus reflectometry principles, and the whole thing is built and tested in NI Multisim.
The setup includes a fast edge pulse source, a properly matched source resistance, a lossless transmission line that represents the fibre span, a discrete fault resis-tance that stands in for an impedance break, and then a matched termination to keep things clean. There is also an LED display, though it is visually isolated through a unity gain buffer, so the indicator doesn't load the measurement too much, or at all for that matter.
From the transient analysis, it's shown that a clearly visible reflected pulse shows up at about 2.515 microseconds after the launch pulse. Using that, the fault distance can be estimated as roughly 251.5 metres away from the source. In the calculations, the refractive index of the fibre is taken as 1.5, like assumed in the paper, and then everything follows. Next, the complementary AC sweep analysis, highlights the discontinuity. You can see it through an uneven magnitude ripple and a non linear phase response across frequency range.
Overall, the results suggest that Time Domain Reflectometry TDR concepts can be reproduced in an electrical circuit simulator, in a way that stays sufficiently faithful, while still giving an approachable, easy-to-use computational environment for learning OTDR based fault localisation. This sort of tool also works well for technician training and pre field diagnostic, quick stuff before you go out.
Keywords*: Optical Time Domain Reflectometry (OTDR); Time Domain Re-flectometry (TDR); optical fibre fault localisation; transmission line; impedance mismatch; NI Multisim; reflection coefficient; fibre optic diagnostics.*

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I. Introduction

Optical fibre has become kind of the backbone of modern telecommunication infrastructure, mostly because it has high bandwidth, low attenuation , and it basically shrugs off electromagnetic interference. Service providers like Bharat Sanchar Nigam Limited (BSNL) are using fibre optic links quite a lot to deliver broadband, Fiber-to-the-Home (FTTH), and enterprise connectivity. This is happening across both urban as well as rural India, and the scale is getting bigger all the time. But once these networks expand, real physical trouble like cable cuts, mis aligned connectors, bending losses , and dust contamination, start showing up more often. So to keep downtime shorter, and maintenance costs low, technicians really need a fast and accurate way to figure out where things break.

That's where the Optical Time Domain Reflectometer (OTDR) comes in. The OTDR generally works by launching a light pulse into the fibre, and then observing the reflections that come back from damages or even from joints. In principle it can pinpoint a fault down to the meter, but the catch is the hardware is very expensive. Because of that cost, most engineering students end up learning the theory in class, and very rarely they get actual, hands on experience with the real circuitry.

We built an electrical version of an OTDR using basic circuit components, like pulse generators and transmission lines , and we simulated the whole thing entirely in NI Multisim. Voltage waves on an electrical wire follow almost the same math as light pulses in a fibre , in the sense that they share the same physics behind reflection coefficients and travel delays. So this electrical model acts as a cheaper, clearer, and more flexible alternative for classroom use. This paper describes the circuit setup, walks through the Time Domain Reflectomeetry (TDR) idea, and then discusses the results in both the time domain and the frequency domain. We also validate the setup by successfully locating a simulated 470 Ω fault on a known transmission line.

A. Motivation and Scope

Conceptualization of this project began somewhat from a six-week internship at the National Institute of Advanced Manufacturing Technology at Ranchi. It was at that time when I had hands-on experience with optical fiber communication network where I realized there is an actual need of having a quick, and low cost method for fault detection before resorting to the costly process of using OTDR. To keep everything in order, therefore, this paper will limit itself to locating only one single fault where such fault is characterized by an abrupt change in impedance. Discussion about other aspects like line losses and overlapping faults will be made in section VIII.

II. Optical Fibre and the Principle of Total Internal Reflection

An optical fibre is made up of three regions: (i) the core, which is sort of a central glass or plastic region with a higher refractive index and that's where the light mostly propagates; (ii) the cladding , this is a surrounding optical layer with a lower refractive index , and (iii) the jacket or buffer coating which is an outer protective skin, it primarily protects against moisture and mechanical damage, like a shield, kind of.

Light gets kept inside the core because of Total Internal Reflection (TIR). It occurs when light going from a denser medium into a rarer medium hits the boundary at an angle that's bigger than the critical angle, so instead of refracting out, it comes back as a full reflection.

For TIR to really take place, you need two main conditions: (1) the ray has to travel from an optically denser medium to an optically rarer medium , and
(2) the incidence angle at the core–cladding interface must be greater than the critical angle. That critical angle depends on the two refractive indices. Figure 1 shows the concept , it basically means that a light ray arriving with an incidence below the critical angle gets transmitted or absorbed into the jacket area and so it is lost, but rays with an incidence above the critical angle keep bouncing through repeated total internal reflection , and they stay guided along the fibre.

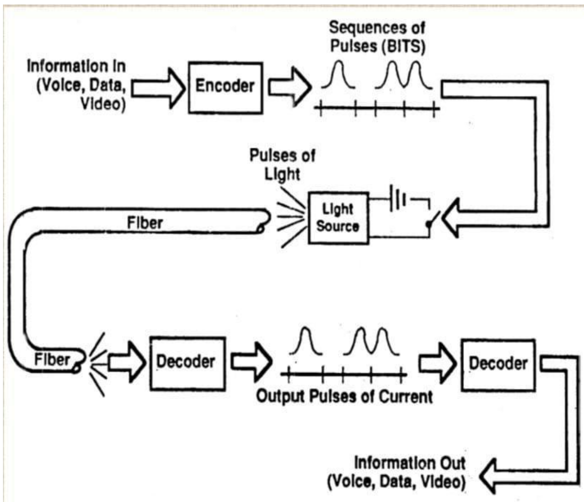

Fig. 1. Structure of an optical fibre and the principle of Total Internal Reflection (TIR) at the core–cladding interface.

Transmission of signal over a fibre-optic link (Fig. 2) is carried out through several steps. Information is first encoded as a series of bits that are then converted to light pulses by a light source like a laser diode or LED. The light pulses travel in the fibre until they are converted back to electrical signals by a photodiode and decoded to form an output. A physical disruption anywhere along this line, for example, a breakage of fibre, poor coupling of connector, bending of fibre or contamination, results in change of local impedance and reflects some light energy back towards the source.

III. Time Domain Reflectometry: Theoretical Ba-sis

The Time Domain Reflectometry (TDR) is the generic electrical principle that forms the basis of OTDR. In TDR, a high-speed pulse of the rising edge type is injected into a transmission line having characteristic impedance Z . If the line is uniform and perfectly terminated, the pulse travels through the line and is totally absorbed at the other end with no reflection occurring. If there is any impedance mismatch of Z , then a part of the pulse will be reflected according to the reflection coefficient

$$\Gamma = (Z \; - Z\,) \,/\, (Z \; + Z\,),$$

where a positive Γ (Z > Z , similar to the condition for an open circuit or high impedance fault) causes a reflected wave with the same polarity as the incoming wave, while a negative Γ (short circuit type of fault) causes a phase inversion. In an optical fiber, the equivalent discontinuities would be the Fresnel reflections at the glass-air interfaces (fiber breakage or unmated connectors), and the Rayleigh scatter enhanced at the point of loss (bending, splice).

The round trip time delay Δt for the outgoing and the incoming pulses is directly proportional to the distance from the fault location, given by

$$Distance = (v \times \Delta t) / 2,$$

Where v is the velocity of propagation of the wave in the medium. In the case of an electrical transmission line, the velocity of propagation v is a function of the dielectric characteristics of the transmission line itself. In the case of an optical fiber, the value of v is estimated by the formula $v = c/n$, where c is the velocity of light in a vacuum (3×10^8 m/s), and n is the refractive index of the core of the optical fiber, which is about 1.5 for the typical silica fiber. But what really makes the point is that the not-so-trivial mathematics of the reflection coefficient, return time delay, and distance-time relationship are essentially identical, not merely similar. Thus we may use the electrical circuit to create a faithful replica of the optical fault localization.

IV. Proposed Circuit: Design and Architecture

We built the proposed optical fiber fault localization circuit using the NI Multisim as an electrical equivalent of an OTDR measurement setup. The design consists of a pulse source, an impedance-matched source resistance, a transmission line that is a replica of the fiber span, a lumped fault resistance, a matched far-end termination, a buffered LED fault-indicator branch, and a dual-channel virtual oscilloscope to capture the transient behaviors.

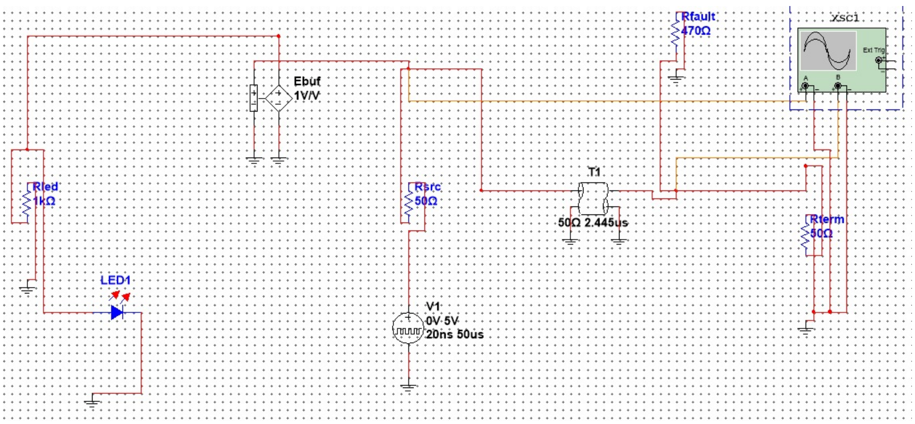

Fig. 3. Full NI Multisim schematic for the optical fiber fault localization setup. The diagram shows the pulse source (V1), source resistance (Rsrc), transmission line (T1), fault resistance (Rfault), termination resistance (Rterm), buffer (Ebuf), LED indicator path (Rled, LED1), and the dual-channel oscilloscope (XSC1).

A. Component Description and Functional Rationale

Table I gives the overview of each component, its assigned values and their functional roles in the circuit

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Compo-nent	Symbol	Value / Type	Functional Role
Pulse Generator	V1	0–5 V, 20 ns rise, 50 µs period	Generates the digital launch pulse to mimic a fast optical source edge.
Source Resistance	Rsrc	50 Ω	Matches the source to the transmission line's characteristic impedance, preventing near-end reflections.
Transmis-sion Line	T1	50 Ω, 2.445 µs delay	Represents the optical fibre and it introduces propagation delay proportional to the length.
Fault Resistance	Rfault	470 Ω	Simulates a physical fiber break, connector loss or any discontinuity via impedance mismatch.
Termination Resistance	Rterm	50 Ω	Absorbs incoming energy at the far end to stop unwanted reflections from the end of the line.
LED with Series Resistor	LED1, Rled	LED, 1 kΩ	Gives a clear visual indication when an active or reflected pulse passes through, making it useful in lab demonstrations.
Voltage Follower (Buffer)	Ebuf	1 V/V unity gain	Isolates the LED indicator branch from the main measurement path to prevent loading effects.
Oscilloscope	XSC1	Dual channel	Captures the sent and reflected waveforms for transient-domain fault analysis.

TABLE I. Component Summary of the Optical Fibre Fault Localisation Circuit

The selected 50 **Λ** values for Rsrc, the T1 and Rterm is to match the standard characteristic impedance used in coaxial and controlled-impedance transmission lines. This choice improves the power transfer and cuts out unwanted reflections under normal, matched conditions, completely aligning with transmission line theory. We deliberately picked a 470 **Λ** fault resistor to introduce a large impedance mismatch ($\Gamma > 0$). This effectively models a high-loss discontinuity, like an open splice or a sharp bend, generating a clear, readable reflection pulse for our fault-detection tests.For the indicator branch the 1 k**Λ** series resistor limits the forward current to a safe level during a 5 V logic swing while keeping the LED bright enough to see easily. Meanwhile, the unity-gain buffer (Ebuf) isolates this indicator pathway so it does not draw power from the main reflectometry signal line.

V. Simulation Methodology

The simulation in NI Multisim is done using the following steps:

1. Transmitter setup: We set the pulse source V1 to an initial level of 0 V, a peak of 5 V, a nanosecond-range rise/fall time, a pulse width of 20 ns, and a period of 50 μs. These parameters mimic

standard digital logic levels while offering a sharp enough edge to resolve short propagation delays.

1. Line and fault placement: We configured the transmission line (TLIN) component with a characteristic impedance of $Z = 50$ **Λ** and a propagation delay of 2.445 μs, which corresponds to a physical fiber span spanning hundreds of meters. We then tied a 470 **Λ** fault resistor from an intermediate node to ground to simulate a localized break.
2. Receiver and indicator: We terminated the far end of the line with a 50 **Λ** characteristic impedance (Rterm) to kill off far-end reflections, ensuring that any captured reflections come mainly from the fault. The buffered LED branch provided real-time visual tracking of the pulse activity.
3. Transient Analysis setup: Under Simulate → Analyses → Transient Analy-sis, the start time (TSTART) was set to 0 s, the stop time (TSTOP) to 200 µs, and a maximum time step (TMAX) of 10 ns was to maintain high timing resolution for the reflected pulse
4. Output variable selection: Under the Output tab, we added the node voltages V(2) (launch/near-end node), V(3) (far-end/fault node), and V(out) (buffered LED branch) to our analysis variable list.
5. Execution and observation: We ran the simulation and checked the resulting waveforms using the built-in NI Multisim Grapher View, utilizing the cursor tool to pull exact timestamps for the launch pulse and its matching reflection.
6. Frequency-domain corroboration: We also ran an AC Sweep analysis across the same nodes to independently check for the fault by looking at how it alters the magnitude and phase responses.

VI. Results and Analysis

A. Transient Response and Fault Signature

The figure below illustrates the output of transient analysis as shown on the NI Multisim Grapher view where the plotted voltages are V(2) and V(3) as a function of time for a 200 µs interval. The graph exhibits a spike of the launching pulse with periodic secondary pulses appearing at about 40 µs apart which is the repetition interval of the pulse generator along with each main pulse followed by a smaller reflected pulse.

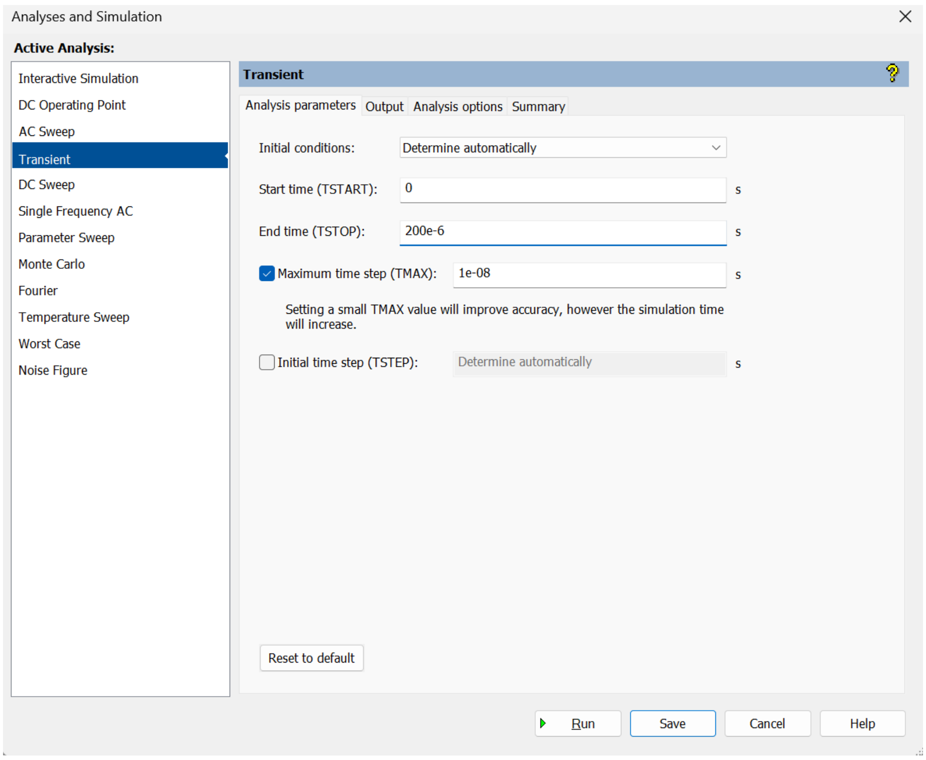

Fig. 4. Transient analysis setup

From a physical point of view, our interpretation is that had the simulated fiber optic cable been free of any defects and terminated in an ideal manner, the values of V(2) and V(3) would follow each other without fail, with just the delay of the transmission line in between and without generating additional pulses.

Here, having two pulses superimposed upon the launch signal unambiguously indicates an impedance mismatch along the transmission line. This is precisely the characteristic we should see for the presence of the fault resistance of 470 **Λ**. It is evident, judging from the repeated nature of these reflections throughout the whole time interval (at 40, 80, 120 and 160 μs corresponding to the 50 μs period of the source) that the mismatch is indeed part of the structure of the line.

B. Precision Timing and Distance Calculation

To find out the exact fault location, we used the Multisim cursor tool to get the exact timestamps for a single launch-and-reflection pair.

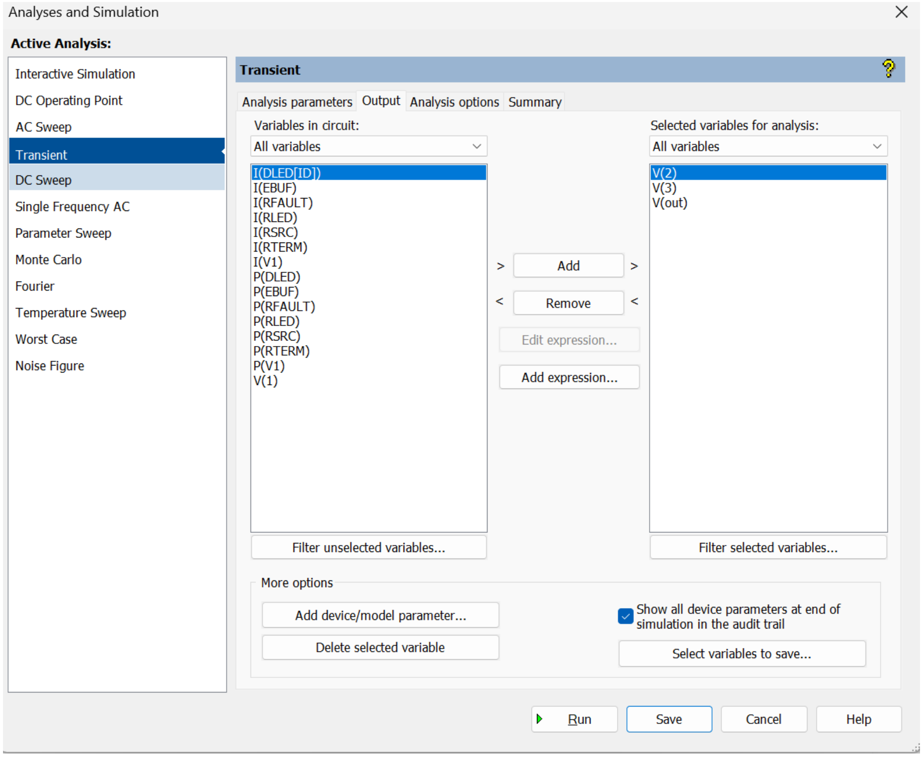

Fig. 5.Parameters selection in the Transient setup.

The cursor readings gave a launch pulse time of t = 49.9727 µs and a reflection arrival time of t = 52.4877 µs, yielding a round-trip delay of:

Δt = t − t = 52.4877 μs − 49.9727 μs = 2.515 μs = 2.515 × 10 s.

C. Frequency-Domain (AC Sweep) Corroboration

As an independent check, an AC Sweep was performed to observe magnitude and phase response of the fault node relative to frequency (Fig. 6).

Assuming a typical silica-fibre refractive index of n = 1.5 and free-space light speed c = 3 × 10 m/s, the effective propagation velocity within the fibre is:

v = c / n = (3 × 10) / 1.5 = 2 × 10 m/s.

Substituting into the distance relation gives the one-way distance to the fault:

Distance = (v × Δt) / 2 = [(2 × 10)(2.515 × 10)] / 2 = 503 m / 2 = 251.5 m.

This calculation demonstrates, at circuit level, the same distance-from-time-delay methodology used by commercial OTDR instruments in the field.

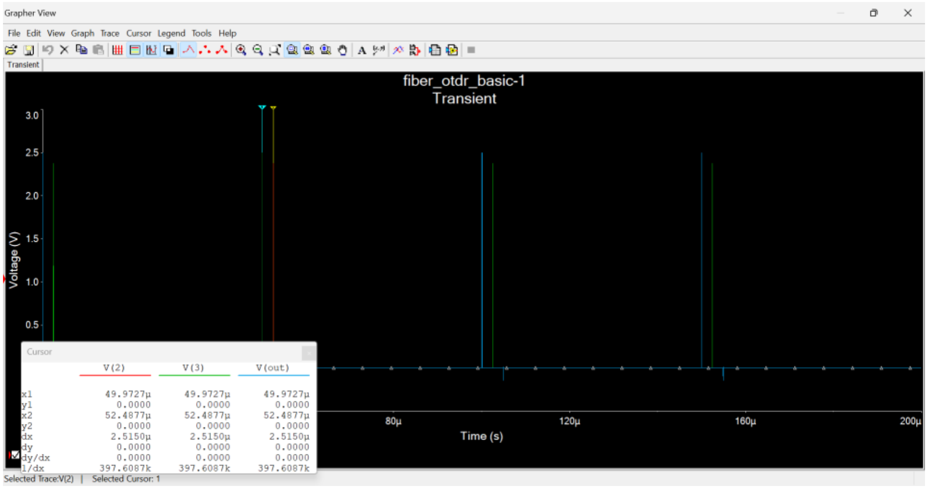

Fig. 6. AC sweep magnitude and phase response at V(2), V(3), and V(out), showing ripple and non-linear phase behaviour characteristic of an impedance-mismatched line.

A properly matched transmission path should have a flat magnitude response and a linear phase response with frequency, indicating a constant propagation delay. In contrast, the faulty node trace in the acquired sweep has significant ripple in its magnitude and a distinctly non-linear, multi-inflected phase response for higher frequencies. Such a ripple response is indicative of a standing wave generated by multiple reflections due to impedance changes in the form of the source-line and fault discontinuities. The agreement between the two methods independently confirms that the fault detected in the time domain (transient analysis) is indeed the fault modeled, not an artifact of the simulation.

D. Summary of Findings

Parameter	Measured / Computed Value
Launch pulse timestamp	49.9727 µs
Reflection arrival timestamp	52.4877 µs
Round-trip delay, Δt	2.515 µs
Assumed fibre refractive index, n	1.5
Effective propagation velocity, v	2 × 10 m/s
Computed fault distance	251.5 m from source
Frequency-domain corroboration	Magnitude ripple + non-linear phase confirm mismatch

TABLE II. Summary of Transient and Frequency-Domain Fault Lo-calisation Results

VII. Discussion

A. Correspondence to Real OTDR Behaviour

The behaviour that is simulated by this electrical circuit is directly related to physical phenomena taking place in actual optical fibres. Reflection of light due to Fresnel reflections from glass-air boundaries such as unmated connectors, end faces of fibres, and clean cuts would be analogous to an abrupt impedance change represented by the resistance Rfault and will cause a distinct reflection. However, Rayleigh scattering is better represented as distributed losses on the transmission line rather than as a lumped resistance-an aspect which will be discussed later.

B. Practical Value for Field Technicians

Since the circuit consists of simple components – pulse generator, resistors, a transmission line, a buffer, and LED – it is possible to build the circuit, simulate, and explain the principle behind its operation without the use of an actual OTDR. This would make the circuit a useful idea for: (i) preliminary screening idea before spending expensive OTDR time on the suspected problem area; (ii) a training and demonstrative tool for new engineers to gain insight into the concepts of delay, matching and reflections and (iii) a bench top equivalent of OTDR for teaching fiber optic transmission line theory.

C. Limitations

- The model takes into account only one discrete fault as a concentrated resistive discontinuity; multiple faults and distributed attenuation are not considered.
- Since we use the fixed refractive index (n = 1.5), we get a representative value of silica fibre. However, the accuracy of actual distances will depend greatly on the type of the fibre you use, which means that you have to calibrate your computations to manufacturer's specifications.
- The refractive index (n = 1.5) is a representative value for silica fibre; actual distance accuracy in a real environment depends on the exact index of the fibre type used in the transmission, which should be properly calibrated.
- The buffer and LED branch is isolated using a unity-gain follower, but is still an idealized model; a real circuit implementation would be required in order to take into account the bandwidth and slew-rate limitationsof an op-amp at these short pulses.

VIII. Advantages and Future Scope

Moving past this single-fault demonstration, the electrical-analogue method used here offers several practical benefits and logical upgrades for future work, which we summarize in Table III.

Advantage / Extension	Description
Low-cost diagnostics	Provides an inexpensive alternative for technician training and quick pre-OTDR fault screening.
Visual/intuitive learning	Helps field engineers directly visualise how electrical reflections correspond to optical reflections in real fibre systems.
Multiple-fault modelling	Future versions could cascade several fault resistances along the line at different delays to emulate multi-fault fibre spans.
Automated distance readout	Cursor-based timing extraction could be automated via a scripted peak-detection algorithm to remove manual measurement error.
Hardware prototyping	The circuit could be realised on a physical benchtop using discrete pulse generators and coaxial delay lines for a hands-on training kit.
Distributed-loss modelling	Replacing the single lumped Rfault with a distributed RC ladder could better emulate continuous Rayleigh-scattering loss along the span.

TABLE III. Advantages of the Proposed Approach and Directions for Future Work

IX. Conclusion

The simulation results for a low-cost analogue-electrical circuit for optical fibre fault localisation have been presented, which has been developed solely using NI Multisim, based on the same Time Domain Reflectometry principle which is also used by OTDR instruments commercially available. The results obtained have been verified independently by AC Sweep (Frequency domain) analysis, where magnitude ripple and non-linearity of phase were observed, which is indicative of impedance mismatch on the line. The very close agreement between the electrical circuit analysis and physical phenomena behind optical fiber reflectometry clearly indicates that transmission-line circuit simulation is a valid, economic and educationally efficient method of replacing OTDR based fault detection. This approach to the testing can be very practical for technician training, preliminary diagnosis and lab classes in telecom industries like BSNL. And it serves as a very good base for development of more complex simulations considering multiple faults and line losses in future.

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