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Superluminal propagation and information transfer: A statistical approach in the microwave domain

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ABSTRACT

Signal velocity is calculated in a medium with negative group delay (NGD). By accounting for the medium and the detector noise sources, the time varying probability of error at the detector [$Pe(t)$] is evaluated in the NGD channel and a normal dispersion channel. The scheme in which $Pe(t)$ falls below a threshold at earlier time, implies faster information transfer. It is found that the signal velocity depends on the detector type and the relative noise strength of the detector with respect to the channel. Finally, it is shown that NGD channels can be useful in applications that are limited by the detector noise.

1. Introduction

An electromagnetic pulse in a temporally dispersive medium can experience non-uniform scaling and phase delay during propagation. Accordingly, a pulse can undergo significant reshaping depending on its spectral characteristics, carrier frequency and temporal support. A special class of interest, in which the velocity of the pulse peak (group velocity) can become superluminal or even negative, is known as abnormal dispersive media. Abnormal group velocity and, equivalently, abnormal group delay (AGD) have been investigated in many studies. For instance, at microwave frequencies, superluminal evanescent tunneling has been demonstrated and compared to quantum mechanical predictions [1–7]. At optical frequencies, double resonance gain-assisted media have been utilized to achieve negative group velocities with minimum pulse distortion [8–12]. Superluminal tunneling has also been reported in the single photon limit [13–16]. It is now well established that AGD is in full compliance with the fundamental requirements of Einstein's causality and can be attributed to dynamical pulse reshaping [17–24] and redistribution of energy during propagation [25,26].

Superluminal (and negative) propagation has naturally been studied in the context of fast information transfer [8–12]. In this context, it has been well known that superluminal signaling is not possible for many reasons. First, from a fundamental point-of-view, genuine information is encoded in the points of non-analyticity (the transitional turn-on) at the front of a causal pulse [23]. These singularities are comprised of high frequency components that lie above the anomalous dispersion cut-off and, consequently, the front velocity remains strictly luminal [15]. Second, even for the cases in which the pulse (typically a Gaussian pulse) is superluminal, it has been shown that the pulse behavior could have been analytically extrapolated from earlier time samples [20,23]. Accordingly, information velocity is not tied to the superluminal effect of the group velocity [17,18,23,24].

2. Motivation

In some situations, it has been practically possible to associate information with the propagation speed of the strictly luminal points of non-analyticity (discontinuities) in a causal pulse, when these points lie above the detection threshold [10,27–31]. However, this is not entirely valid under all circumstances. In many other practical situations, the energy content of the precursor oscillations associated with the pulse front is typically submerged below the noise floor which makes its reliable detection non-practically feasible [1,23]. In such cases, it is not straight-forward to associate information with the propagation speed of the (practically undetectable) front. Instead, information should be associated with the time instant at which the detector device receives a sufficient amount of energy that is distinguishable from the noise floor. As such, one cannot quantify the signal velocity (or equivalently signal

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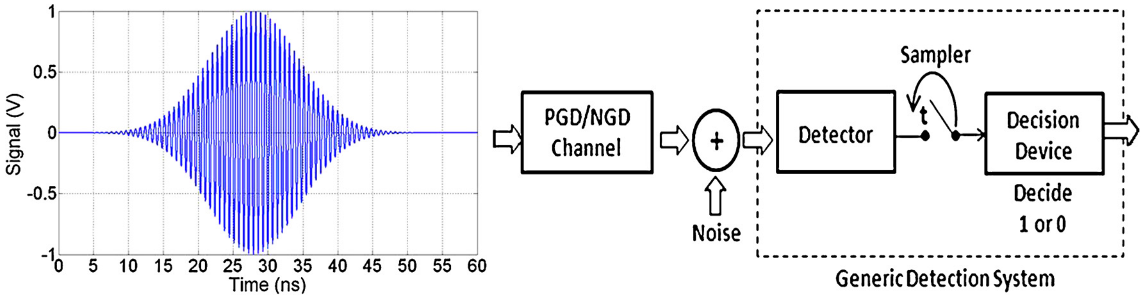

Fig. 1. A schematic diagram of the proposed thought experiment. (a) A 1.45 GHz modulated Gaussian pulse with FWHM of 15 ns is applied at the input of NGD and PGD channels. The channel noise is added before the detection process.

delay) without considering the contributions of the noise generated in the medium and the detector.

The goal of this paper is to: calculate signal velocity in any dispersive medium, investigate the possibility of utilizing an AGD medium to reduce signal detection latency and, finally, to set constraints on the detector and the medium so that such latency reduction can be achieved. Although previous efforts have been made in this area [10,32–35], there are two key distinctions here:

First, in this study, we investigate the behavior of signal velocity while considering three different detection schemes at the receiver side; these are: the correlation detector, envelope detector and matched filter detector. While the correlation detector and the envelope detector have been previously considered in the literature to probabilistically characterize the signal velocity [10,32–37]. Here, we are rather interested in the limitations imposed by the detector noise and its effect on the signal velocity. In each detection scheme, we study the behavior of signal velocity under various noise profiles. It is shown that not only the detector type but also its noise characteristics determine whether signal detection latency can be reduced or not. This sets fundamental constraints on the detection scheme (type and associated noise) under which signal detection latency can be reduced.

Second, a strict condition applies here when comparing our results to a medium with positive group delay (PGD); unlike many previous studies [33–35], the dispersive medium (channel) is carefully tuned so that the overall energy exiting from both channels is kept the same. This guarantees that any fast information transfer is not attributed to excess energy from the medium, and ensures fair comparison with the positive group delay (PGD) medium.

As such, this analysis aims at showing the capabilities as well as presenting the limitations of signaling schemes that utilize superluminal (or negative) group delay.

This paper is organized as follows: in Section 3, we present the statistical approach for quantifying information latency in a general dispersive medium. In Section 4, we consider an active microwave NGD circuit as a case study and we account for its respective noise contribution. In Section 5, the important role of the detector is emphasized as we consider three different detection systems: the correlation detector, the envelope detector and the matched filter. Additionally, each detector is studied under three different noise profiles. Finally, we discuss the practical feasibility of utilizing AGD media to reduce information latency.

3. Approach

In any noisy communication system, there exists a non-zero probability of encountering errors in the detected signal. Therefore, reliable detection of information can only be described probabilistically. A standard metric that is used to quantify reliable information detection, without loss of generality, is the probability of error (P_e). This is the probability that a bit is incorrectly identified. In this thought experiment, P_e is the probability that either the receiver decides that a pulse has been sent when, in fact, it has not, or the receiver fails in detecting an actual transmitted pulse. Given the detection system in addition to the energy content of the pulse and the associated noise floor, the probability of encountering errors in the detection process can be written in well-established closed form expressions [38]. Therefore, reliable detection of information can analytically be quantified.

In order to calculate the probability of error in the detected signal, one has to consider the full communication system. The scheme used in our thought experiment can be described as follows: a microstrip transmission line is divided into two equal sections and loaded with an NGD active circuit in the middle of the two sections. At time instant ($t = 0$), the channel is either excited by a signal represented by a causal, modulated Gaussian pulse (bit 1) or not excited at all (bit 0). This scheme represents a simple on-off keying (OOK) communication protocol. The generated pulse is then processed at the receiver which consists of a detector, a sampler, and a decision device as illustrated in Fig. 1. The noisy detection apparatus at the receiver end attempts to determine as quickly as possible whether or not a signal has been sent. The same configuration is applied to the case of a conventional PGD microstrip line for comparison.

Instead of sampling the output of the detector at only a single time instant at which the SNR has a maximum value as in conventional communication systems, the output is sampled continuously as a function of time herein. Accordingly, $P_e(t)$ can be described and calculated as a function of time. The time instant at which $P_e(t)$ falls below a preset threshold (equivalent to the SNR exceeding a preset threshold) implies that the pulse (new information) has been reliably detected within the limit of the preset threshold. The time required to reach the threshold defines the signal delay. This approach is applied in details in Section 5 while considering three different detection schemes; the correlation detector, the envelope detector and the matched filter detector.

In order to calculate $P_e(t)$, the noise generated in the medium should first be obtained. As such, in the next section, we introduce the NGD channel and calculate its noise contribution and output field.

4. Channel analysis

The active NGD circuit proposed by Ravelo et al. [39,40] is adopted in this analysis. The circuit is composed of two cascaded cells consisting of a parallel connection of a PHEMT transistor and a series RLC branch. This topology realizes NGD in addition to possible input/output matching. Fig. 2 shows a schematic of the NGD channel in which a microstrip transmission line is cut into two symmetric sections and loaded with the NGD circuit in the middle.

The circuit considered by Ravelo, however, exhibits gain. In the present analysis, the active circuit is tuned to obtain overall unity channel gain. In that case, the output pulse undergoes reshaping