Limited-Diffraction Beams for Secure Fast Data Communications

Jian-yu Lu
The University of Toledo, Toledo, Ohio, USA
Email: jian-yu.lu@ieee.org

***Abstract* – X wave is one of the limited-diffraction beams and was developed in 1992. It is an exact solution to the linear isotropic/homogeneous or free-space scalar wave equation. X wave can be highly localized with a sharp center peak in both transverse (perpendicular to the wave propagation) and axial (along the wave propagation) directions in the three-dimensional (3D) space, and in theory, can propagate to an infinite distance without changing its shape. In addition, both the group and phase velocities of the X wave are always larger than the speed of sound (supersonic) or the speed of light (superluminal).**

Because of the localization property and the supersonic group velocity, in this paper, the X wave was used to transmit digital information (or energy) at a supersonic speed for secure and high-speed data communications in multiple channels. Both computer simulations and experiment were conducted using a 2.5-MHz ultrasound transducer in water. The results show that even with a finite transducer aperture, the X wave has a very large depth of field and is nondispersive (the wave speed does not change with the temporal frequency). As a comparison, Bessel pulses also were used for multi-channel data communications. However, Bessel pulses are dispersive, which lowers the data transmission rate. Despite of this disadvantage, the Bessel pulses have an adjustable group velocity that is always slower than the speed of sound (subsonic) in the isotropic/homogeneous media or the speed of light (subluminal) in free space (or vacuum). Thus, the Bessel pulses can be used as a delay line in a way similar to the surface acoustical wave (SAW) devices but with an adjustable delay time.

Since the ultrasound experiments show that X wave can transmit digital information at a supersonic speed and the ultrasound X wave shares the same wave equation as the light or electromagnetic waves, X wave also can transmit information at a speed that is greater than the speed of light in free-space or vacuum. In 2023, the author has developed X wave solutions to the free-particle Dirac, Klein-Gordon, and Weyl equations in quantum mechanics. Given the superluminal group velocity of these X waves, it is possible that both the massive and massless particles can be used to transmit information (energy) at a speed that is larger than the speed of light in free space or vacuum.

Keywords – ***X wave; Bessel pulses; limited-diffraction beams; scalar wave equation; quatum mechanics; free-particale Dirac, Klein-Gordon, and Weyl equations; supersonic, superluminal, information or energy transmission, communications, multi-channel.***

I. INTRODUCTION

Waves that are localized in space have been studied over past several decades; see a recent review paper in Ref. [1] and books dedicated to this topic [2]-[3]. These include Bessel beams [4]-[7], Bessel pulses [8]-[14], localized waves [15]-[16], X wave [17]-[20], and related studies in electromagnetics and microwave [21]-[26], optics [27]-[35] (including Airy beams [36]-[38]), and quantum mechanics [39]-[43].

Among the waves that are localized, X wave has attracted a special attention after it was developed in 1992 [17]-[18]. X wave is an exact solution to the linear isotropic/homogeneous or free-space scalar wave equation. It is polychromatic (containing multiple temporal frequencies) and can be highly localized with a sharp center peak in both transverse (perpendicular to the wave propagation) and axial (along the wave propagation) directions in the three-dimensional (3D) space, and in theory, can propagate to an infinite distance without changing its shape. Both the group and phase velocities of the X wave are always larger than the speed of sound (supersonic) or the speed of light (superluminal).

Because of the spatial and temporal localization property and the supersonic group velocity, in this paper, the X wave was used to transmit digital information (energy) at a supersonic speed for multi-channel data communications. Both computer simulations and experiment were conducted using a 2.5-MHz ultrasound transducer in water. The results show that even with a finite transducer aperture, the X wave has a very large depth of field and is nondispersive (the wave speed does not change with the temporal frequency and thus the pulse shape does not change as the wave propagates). The multiple channels increase the data transmission rate significantly and enhance the communication security since a piece of digital information can be distributed among different channels and the signals will be naturally scrambled at distances larger than the depth of field due to diffraction. Because the X wave has a 3D shape and a high transverse localization, if N channels are packed into each of its perpendicular transverse directions, there will be a total of $N \times N$ channels, which increase the data rate by N^2 folds without significantly increasing the transducer aperture. High data rate is desirable for communications in many applications, especially for video signal transmission.

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Since the ultrasound experiments show that X wave can transmit digital information (energy) at a supersonic speed and the ultrasound X wave shares the same wave equation as the light or electromagnetic waves, X wave also can transmit information at a speed that is greater than the speed of light in free-space or vacuum [21][24]. Also, the digital information transmitted must contain energy since the hydrophone used in the ultrasound experiment would not be able to detect a signal if the information arrived did not contain the energy. Notice that the superluminal phenomenon of the X wave has been studied by many researchers [44]-[50]. Despite of their attempted explanations, what is missing from the explanations is that the superluminal phenomenon of the X wave is due to the wave nature of particles in quantum mechanics, i.e., the Heisenberg's uncertainty principle [51], where it states that if the change of the momentum vector of a particle is approaching to zero, the position vector of the particle is undetermined, meaning that the particle can be found with an equal probability density in any place in the 3D space, which is described by a plane wave. Since X wave is a linear superposition of these plane waves (see Section VI. K. "More on the Velocity of the Waves" of Ref [52]), it is formed by a regroup of these particles whose position vectors are undetermined (i.e., the particles are not localized in the space). The regrouped particles will appear with the highest probability density at the peak of the X wave that travels at a speed greater than the speed of light in vacuum along the axial direction of the X wave (notice that the X wave is polychromatic, meaning that it is formed by particles of different energies and thus the plane waves that form the X wave is localized in time although they are not localized in space). Recently, X-wave solutions to the free-particle Dirac, Klein-Gordon, and Weyl equations in quantum mechanics were obtained (see Section VI. L. "deBroglie Waves" of Ref. [52]). Given the superluminal group velocity of these X waves, it is possible that both the massive and massless particles can be used to transmit information (energy) at a speed that is greater than the speed of light in free space or vacuum. This is consistent with the quantum entanglement experiments [53]-[55] that show the particles follow the quantum mechanical instead of deterministic [56] rules. Thus, the superluminal transmission of information (energy) by X wave is just a natural phenomenon that can happen in our universe under certain conditions. Thus, the ultrasound X wave experiment presented in this paper and the paper in Ref. [52] is another proof that the quantum mechanics is correct and there is no "hidden" variable in the quantum entanglement.

II. Simulation, Experiment, and Results

Both computer simulation and experiment were conducted for multi-channel communications with the X wave. As a comparison, Bessel pulses were also studied. The details of the simulation and experiments were given in Sections III "Computer Simulation", IV "Experiment", and V "Results" of Ref. [52]. Below are the main results:

Figs. 1 and 2 respectively show the computer simulation and experiment results of the X wave by placing three communication channels in the x direction that is perpendicular to the propagation axis (z axis). Three binary codes "1001", "1011", and "1111" (read from right to left) were transmitted simultaneously through three channels (lower panels). As a comparison, a spherical wave (produced by a transducer of 2-mm radius) that transmitted a single binary code "1011" is shown on the top panel. The center frequency of the transducer was 2.5 MHz and its fractional bandwidth was about 81% of the center frequency. Other parameters are shown in the figures. The depth of field of the X wave was about 357.52 mm, i.e., the binary codes in the figures can keep their shapes from $z = 0$ to 357.52 mm. This is different from the spherical wave that can only transmit a single channel of data since it diffracts as it propagates. Because the beams are axially symmetric, channels also can be added in the y direction to increase the number of channels to, say, 3x3 = 9. From the figures, it is clear that the velocity of the X wave is about 0.275 μs (or 0.243%) faster (see the vertical lines) than the spherical wave that travel at the speed of sound. As mentioned in the "Introduction" section, the X wave solutions for particles are superluminal and thus both the simulation and experiment results in ultrasound suggest that the particle X waves can be used to transmit information (energy) faster than the speed of light in vacuum [52].

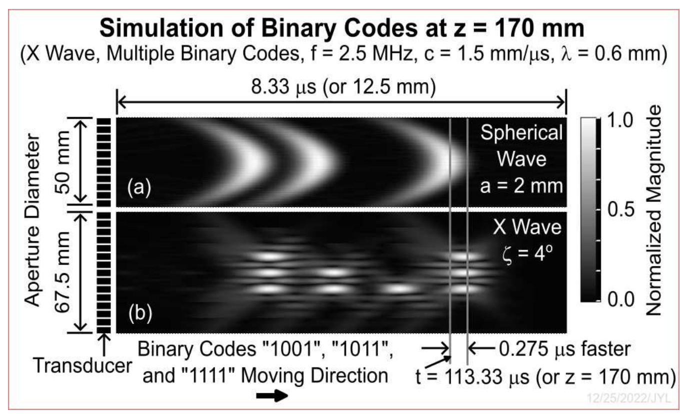

Figure 1. Computer simulation for multi-channel digital communications with supersonic X wave [52]. The digital information is encoded into the peaks of the X wave. The thick arrow at the bottom of the figure indicates the wave propagation direction. It is clear that the X wave with the given parameters in the figure travels faster than the speed of sound in water (supersonic) by about 0.275 μs (or 0.243%).

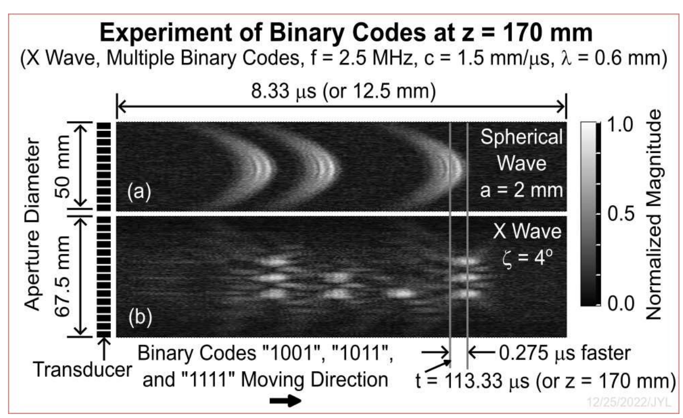

Figure 2. Experiment result corresponding to the simulation in Fig. 1 [52].

Like the X wave, Bessel pulses also can be used for multi-channel data communications over a large depth of field (see Figs. 3 and 4 for computer simulation and experiment results corresponding to Figs. 1 and 2 respectively, with changes of the distance and the transverse localization as shown in the figures) [52]. However, Unlike X wave, Bessel pulses are dispersive and thus the data transmission rate will be lowered as the propagation distance is increased. Despite of this disadvantage of the Bessel pulses, the group velocity of the Bessel pulses is adjustable and is always slower than the speed of sound (subsonic) in the media or the speed of light (subluminal) in the free space (or vacuum). Thus, the Bessel pulses can be used as a variable ultrasound delay line [57]-[59] in a way similar to the surface acoustical wave (SAW) devices [60]-[62] but with an adjustable delay time.

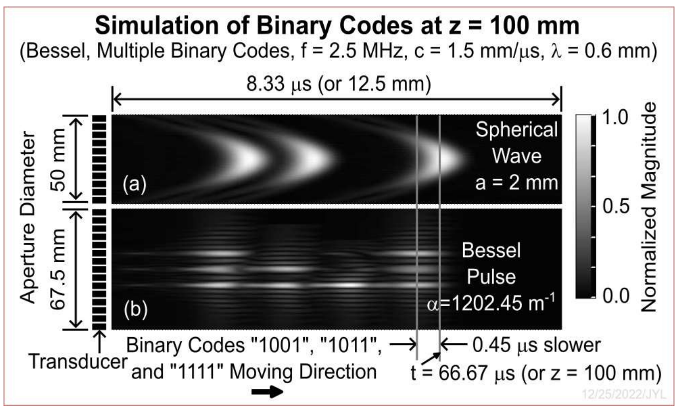

Figure 3. Computer simulation for multi-channel digital communications with subsonic Bessel pulses [52]. The digital information is encoded into the peaks of the Bessel pulses. The thick arrow at the bottom of the figure indicates the wave propagation direction. It is clear that the Bessel pulses with parameters given in the figure travel slower than the speed of sound in water (subsonic) by about 0.45 μs (or 0.675%).

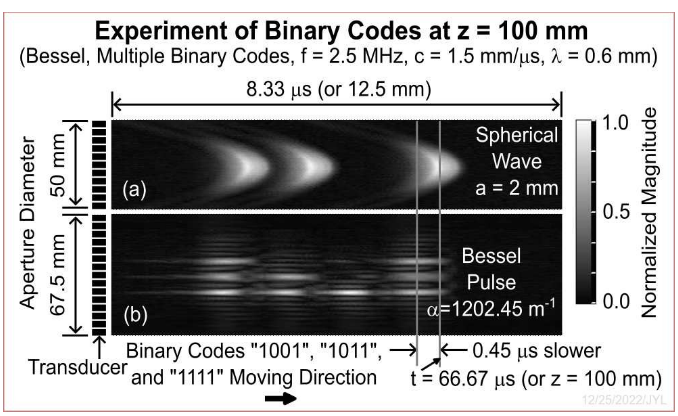

Figure 4. Experiment result corresponding to the simulation in Fig. 3 [52].

III. Conclusion

X wave is highly localized in the 3D space and can be used to transmit digital information (energy) faster than the speed of sound in water (supersonic), as is shown in both the computer simulation and experiment. Thus, the X wave can be tightly packed in space to form multiple channels for secure and high-data-rate communications. Since the electromagnetic, optical, and particle X waves share the same or similar scalar wave equations as the ultrasound X wave, they can be used to transmit digital information (energy) faster than the speed of light in free space or vacuum. In contrast, Bessel pulses always travel at a speed slower than the speed of sound or light since they have a subsonic or subluminal group velocity. This allows the Bessel pulses to be used as a delay line [57]-[62] with an adjustable delay time. However, because the dispersion increases with the delay time, data transmission rate of the Bessel pulses will be limited in such applications.

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