An Overview of Signal Processing with a Focus in Satellite Communication

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Abstract

Signal processing has been used for decades and is prominent in modern technology because it gives scientists and engineers the ability to analyze and optimize data. One important application of signal processing is wireless communication. Wireless communication allows us to communicate without physical connectors, making communication more efficient and accessible. This paper explores the basics of signal processing and wireless communication while also delving into how it can be applied to satellite communication, a sub-field of wireless communication that focuses on communication made possible through artificial satellites. A few ways that satellite communication can be used are for long range communication and radio broadcasting. Though satellite communication has lots of benefits it also has some limitations. We explore some of the limitations of satellite communication and different areas of development in the field that will allow us to improve current technology.

Introduction

Signal processing is a field that has been relevant for much of our technology for decades. It can be applied to many different fields within the Science, Technology, Engineering, and Mathematics (STEM) community in order to allow scientists and engineers to analyze and optimize data. Signal processing is built on the framework of signals and systems. A signal is a function that contains one or more variables (Oppenheim). A system refers to a procedure used to change a signal in order to include the information that needs to be transmitted (Oppenheim). There are three characteristics of a signal that can be changed in order to transmit data. These characteristics are the amplitude, phase, and frequency (Oppenheim). The Fourier Transform is a mathematical tool used in signals and systems that allows various frequencies within a signal to be broken up into separate components. This helps us because we can then analyze the various aspects of a certain signal. In Section 1, we introduce signal processing along with the various characteristics of signals and the Fourier Transform.

In Section 2, we delve into wireless communication. Wireless communication is any form of transmission that doesn't require physical connectors such as wires or cables. Wireless communication is becoming increasingly popular in many technological devices today because it allows users to communicate with ease and provides more mobility because there are no wires restricting movement. Wireless communication is used in Wi-Fi and Bluetooth technologies. Wi-Fi is wireless networking technology that allows devices to access a network wirelessly. Bluetooth is short range wireless technology that allows for data exchange between two close devices. Wireless communication is fundamentally built on signal processing because signal processing enables data to be exchanged between two different devices.

In Section 2, we focus in depth on wireless communication and how signal processing is applied to make data transfer possible. Several techniques used in wireless communication are described in detail, including modulation, transmission, propagation, reception, decoding, and presentation. Modulation is one of the most important steps in the process of wireless communication. This step changes the original signal in order to carry the data that is being transmitted. It is the step in which signal processing is applied and the carrier signal is changed. Because it is such an important step in understanding the process of wireless communication, the two main modulation techniques, analog and digital, are defined and compared. The modulation techniques within these two main categories are also defined and discussed in great detail with diagrams of how modulation affects a signal to help with comprehension.

Wireless communication encompasses many forms of communication with it including cellular, infrared, and satellite communication. Section 3 focuses on satellite communication and the infrastructure used in the process as well as the steps involved. There are two types of satellites, artificial and natural. Natural satellites are satellites that naturally orbit larger masses such as the moon orbiting the earth. Artificial satellites are the ones used for communication purposes and are man-made masses created to orbit larger masses. There is a lot of infrastructure and technology involved in building an artificial satellite for communication purposes because of the distance that data needs to travel between ground level and the atmosphere. Data travels back and forward from ground level to space, necessitating both a ground station and a space station. The ground station is where most of the work happens and data is processed and sent to different areas. Typically, many ground stations are connected to a singular space station. Space stations are much more sparse globally in comparison to ground stations and mainly consist of the satellite. Ground stations and space stations are described in depth in Section 3. The process used to send data up to the satellite and back down to the ground station are also discussed. There is a slight difference is how data is shifted up to a satellite in comparison to how it is shifted down to a ground station because for data to go upward to the satellite, it has to be converted to the uplink frequency whereas for data to go down it has to be shifted to the downlink frequency. This is to link the data properly to either a ground station or space station. Overall, the rest of the steps remain similar for shifting data to a satellite and shifting data to the ground station. We conclude by discussing areas of development in satellite communications and future work in Section 4.

Technology is constantly advancing and today, autonomous vehicles are gaining attention. Autonomous vehicles are vehicles that drive themselves. Though they haven’t been released to the general public, when they do they will hopefully lead to a visible decrease in the amount of car accidents that are caused by intoxicated or distracted driving. Autonomous vehicles rely on satellites for navigation information as well as information on weather changes, traffic patterns, or road conditions. The information sent from the satellite to the vehicle is then used to calculate speed, direction, and the current location of the vehicle. Though satellites do provide a lot of benefits because of all the information they are able to provide and the accuracy and efficiency in transmitting the information, there are some limitations. One of the biggest issues with satellite transmission is signal interference. Environmental factors such as weather conditions or tall structures, like buildings and mountains, can interfere with a signal traveling to its destination causing disruption to the signal. This is harmful because if a signal is disrupted it could stop providing information or it could provide inaccurate information to the vehicle. Because the vehicle isn't under human control, this could lead to flaws in decision making. Another issue is that satellite coverage isn't always available in remote areas. Because of this, if a vehicle travels through a remote area, there could be places where it isn't able to access important navigation information, causing the vehicle to lose track of where it is. These limitations are slowly being addressed by researchers trying to create more sophisticated signal processing techniques and using Low Earth Orbit satellite networks. Overall, this gives a basic understanding of signal processing while delving into an application of signal processing, wireless communication.

We discuss the steps necessary for wireless communication before moving onto satellite communication, a form of wireless communication, and the future of the field. An application of satellite communication that is coming up is autonomous vehicles. We define and explain autonomous vehicles and their relationship to satellites, before moving onto limitations and concluding with a brief summary of all topics discussed throughout the paper.

Signal Processing

Signal processing has been used in several applications, including examples such as Wi-Fi and bluetooth technologies (mobile signal processing), that have been prominent in technology for many decades (Lou). It is important to gain a basic understanding on how signal processing works. Signal processing is a broad field of study that deals with extracting, amplifying, encoding, or deleting information from a signal (Oppenheim). A signal is defined as a function of one or more variables that is used to carry information such as audio, images, and digital data. Signals are typically represented as periodic functions—in other words, sine and cosine waves. Signal processing allows for the manipulation of a function's amplitude, phase, and/or frequency in order to alter the original signal to store desired data. Some examples of signal processing being applied to everyday life include texting a friend a photo or sending an email. By doing these things, data is being transmitted from one device to another. There are endless applications of signal processing in many different fields of study because of its ability to store and transmit information.

Signals and Systems

The theoretical framework behind signal processing is a combination of system and signals. As previously defined, a signal is a function of one or more variables. In this section, we will discuss the essential characteristics of signals that are essential to understanding how they are analyzed and processed. A signal can be decomposed into basic components, with each component described by phase, amplitude and frequency, see Fig. 1.

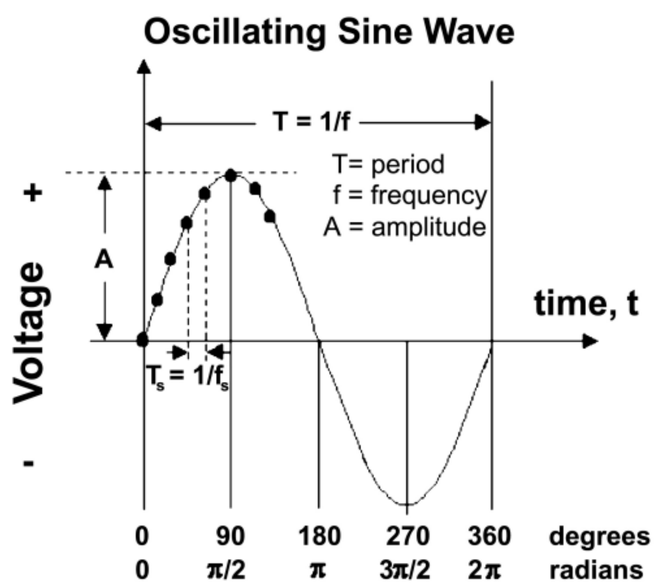

Figure 1: Phase, amplitude, and frequency of a sine wave. Voltage is shown on the y-axis to represent changes in the pressure from an electrical circuit's power source over one cycle of a sine wave.

The phase of a signal refers to the relative position or displacement of a waveform with respect to a reference point, such as the origin, measured in degrees or radians.

The amplitude of a signal refers to the strength or magnitude that a signal carries. The amplitude is used as a reference of the signal's strength and is always positive. The frequency of a signal is referred to the number of oscillations a signal makes in a given period of time. It represents the rate of repetition in a signal and is often measured in Hertz [Hz]. The frequency is found by dividing the number one by the period of the signal; one Hertz is equivalent to $1/$second.

These basic characteristics of a signal (component, phase, amplitude, and frequency) can be manipulated using a system. A system refers to the procedure or device that changes the input signal in order to modulate the data onto the signal. One example of a system is a transformation on a periodic function such as sin or cosine.

EX: $f(x) = cos(x)$ (original signal) → system → $f(x) = 3cos(x) + 4$ (transformed signal)

As shown in the example above, the original function, the signal, is translated 4 units up and vertically stretched by 3 units by the signal. This is what a system typically does,instead of translating the function it changes one of the three characteristics. Signals and systems share an input-output relationship that allows them to be used for analysis and processing.

Continuous Time and Discrete Time

There are two different types of signals within the broad category, continuous time signals and discrete time signals. Continuous time signals are functions that have defined points (continuous) throughout the entire time domain given. They are able to take on any value within their range including real numbers, fractions and decimals. Discrete time signals are functions that only take in integer arguments. They are not defined throughout an entire domain, they are only defined at specific integer intervals.

There are different applications to both continuous time and discrete time signals. Continuous time signals are used for anything in which intermediate values are necessary. An example of this is a voice signal because voice signals have intermediate values that have to be monitored at all times to be properly tracked (Wu). Discrete time signals are applied more often in digital systems where sampling processes are performed to have a number set of discrete values. Both continuous time and discrete time are very similar because it is possible to calculate discrete time values from continuous time signals, as is one key difference, the periodicity. You can tell if a continuous time signal is periodic by looking at the graph or using an equation to see if the intervals line up, but it is a slightly different process for discrete time signals. For discrete time signals, though it may look like the signal is periodic, the frequency has to be an integer for the function to be considered periodic.

Fourier Transform

The Fourier Transform is an important concept in signal processing because it enables signals to be broken into component waveforms. The Fourier Transform is a mathematical tool that allows signals to be converted from the time domain to the frequency domain. This is important to signal processing because a signal can contain many different frequencies that have been combined together to form a singular function. To examine each of these frequencies separately, a Fourier Transform is required to split them apart. This is a general equation that describes a single frequency f; the Fourier Transform breaks any arbitrary signal into an infinite sum of components with different frequency:

$$g(t) = e^{-2\pi i f t}$$

When applying the Fourier Transform in practice, a signal is usually split into smaller windows and then the Fourier Transform is calculated for each segment. Then the windows are combined together to get the frequency representation for the entire signal. Going back from the frequency domain to the time domain, an inverse Fourier Transform can be applied to the signal, see Fig. 2.

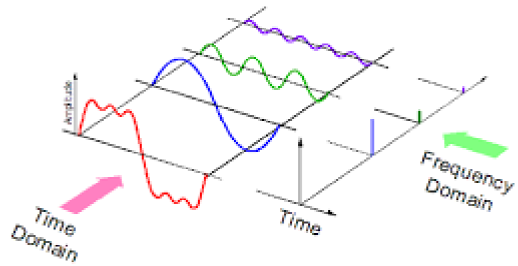

Figure 2: Diagram of the signal broken into various frequency domain components. The time domain is the same for all of the curves but the frequency domain varies.

Wireless Communication

Wireless communication is technology that allows for the transmission of data without the use of physical connectors such as cables and wires. It is becoming increasingly popular in modern technology because it is much more convenient for users to be able to communicate without wires in the way, providing for easier mobility. Signal processing is a large part of wireless communication because it provides for a method to transfer data from one device to another using electromagnetic waves. There are six basic steps that allow for wireless communication, described below.

Modulation

Modulation is the first step in the process of wireless communication. A baseband signal is the name of the signal with information that needs to be transmitted. Modulation is the process of changing one of the properties of the carrier signal (phase, amplitude, and frequency) according to the baseband signal. See Fig. 3 for details.

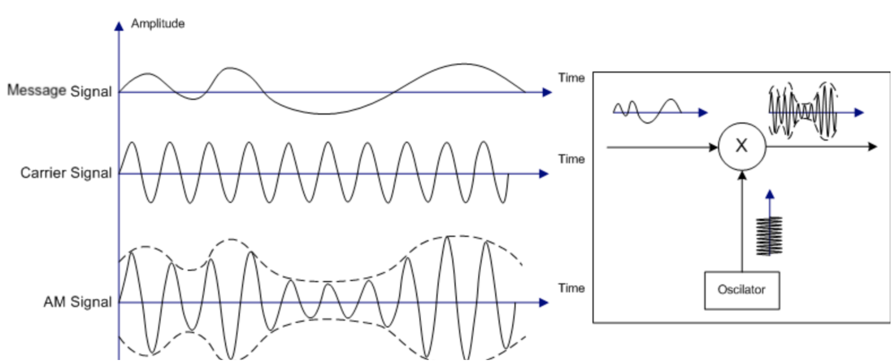

Figure 3: Diagram of Message Signal Being Modulated onto Carrier Signal

Modulation is convenient to use because it helps reduce the antenna size, reduces interference, and allows for the multiplexing of a signal. There are many types of modulations according to what aspect of the carrier signal needs to be changed, the two largest categories of modulation are Analog Modulation and Pulse Modulation.

Analog Modulation

Analog modulation is the process of transferring an analog baseband signal over a high frequency signal. There are different types of analog modulation such as amplitude modulation, frequency modulation, and phase modulation (Herres).

Amplitude modulation refers to the process of changing the amplitude of the carrier wave in order to incorporate the baseband signal. This changes the shape of the carrier wave. Frequency modulation is the process of changing the frequency of the carrier wave in order to incorporate the baseband signal. If the amplitude of the original signal increases, then the frequency of the modulated signal does too, and if the amplitude of the original signal decreases then the frequency of the modulated signal decreases. Phase modulation is the process of changing the phase of the carrier wave in order to incorporate the baseband signal. Analog modulation is often used for shorter distances because it is much cheaper to implement than pulse modulation. For analog modulation, it is unnecessary to have complex equipment and difficult multiplexing, and therefore, it is often used for communication such as radio broadcasting of AM and FM radio stations (Herres).

Pulse Modulation

Pulse modulation is another form of modulation in which message information is encoded within the amplitude of a series of signal pulses. Like analog modulation, there are different types of pulse modulation such as pulse amplitude modulation, pulse width modulation, pulse position modulation, and pulse code modulation.

Pulse amplitude modulation uses the height or amplitude of the pulse signal to transmit information. Pulse width modulation is the process in which the width of the pulse is changed according to the message signal. Pulse position modulation is the process in which the position of the modulated signal will change according to the input signal. Pulse code modulation is when the message signal is sampled at a finite interval and then the data given by the sample is quantized and encoded. Different types of pulse modulation are used to digitally represent analog signals, so it is widely used in the digital world to modulate data in communication systems, control systems, and data transmission.

Transmission

Transmission is the next step in the process of wireless communication and one of the most important steps. Transmission is the process in which data is sent between two devices using radio waves. A transmitter is used to generate the modulated signal and amplify it to a power level that is suitable for wireless transmission. There are many components involved in the transmitter, including an antenna and power amplifier. The goal of transmission is to successfully transmit data over the wireless medium (channel) while reducing the effects of the channel on the wave and maximizing the data quality.

Propagation

Propagation occurs when a radio wave is traveling, or propagating, through the air to its destination. The behavior of the wave is influenced by many factors such as the distance the wave has to travel, environmental obstacles, and the frequency that was used for the radio wave. The wave can be absorbed, reflected, refracted, or diffracted when it encounters other objects (Basic Introduction To Satellite Communications).

Reception

Reception is an important step in wireless communication because it uses the receiving device to capture transmitted data. Reception occurs right after propagation and is when the device receiving the wave uses an antenna to capture the radio waves carrying the transmitted signal and convert the signal back to the electrical signal (Basic Introduction To Satellite Communications).

Decoding

Decoding refers to the process of taking the demodulated signals and then decoding the signals in order to discover the original encoded information. The receiver device then processes this encoded information.

Presentation

Presentation refers to the way that the received information is provided to the user on their technological device. An example of presentation of information is when, during a phone call, audio data is converted back to sound waves and played through the device's speakers.

There are many more substeps involved in the whole process of wireless communication, but these are the essential “milestone” steps that the entire process is based around. The two most important steps, arguably, in the process are modulation and transmission. These are the first two steps in the process that add the baseband signal to the carrier signal and transmit the data to start the process of propagation. If either of these steps are unsatisfactory, there could be severe impacts on the finished result. In the case of modulation, choosing an modulation technique that doesn't fit physical constraints or amplifying the data incorrectly could result in a final signal distorted beyond recognition (Ssimbwa).

Satellite Communication

Satellite Communication is the process in which artificial satellites are used in order to provide communication between two points on Earth. The technology is used in various applications, including radio broadcasting and long distance communication. A satellite is defined as any object that orbits an object that is larger in size. In the category of satellites, there are two types: natural satellites and artificial satellites. Natural satellites are objects in space that naturally orbit a larger object. Some examples of natural satellites include the moon as it orbits the Earth or the Earth as it orbits the sun. Artificial satellites, the type that is important for satellite communication, are satellites that are designed and launched to achieve various purposes such as navigation or weather communication (Elbert).

Satellite Elements

There are two parts to artificial satellites: the ground segment and the space segment. The space segment is primarily made of the satellite whereas the ground station has many aspects such as the earth station, terrestrial network, and the user. The Earth station is the main component of the satellite, the Earth Stations contains all fixed or mobile transmission and reception equipment. Ground stations are also typically equipped with large antennas to send and receive information over long distances. The satellite collects all of the data but the Earth stations process the data. One satellite typically connects to multiple Earth stations as there are many more Earth stations that there are Satellites.

The next element is the Terrestrial Network. The Terrestrial Network plays a role in routing signals from various devices. It is what leads all of the signals from user devices to the transmitting earth station. See Fig. 4 for details.

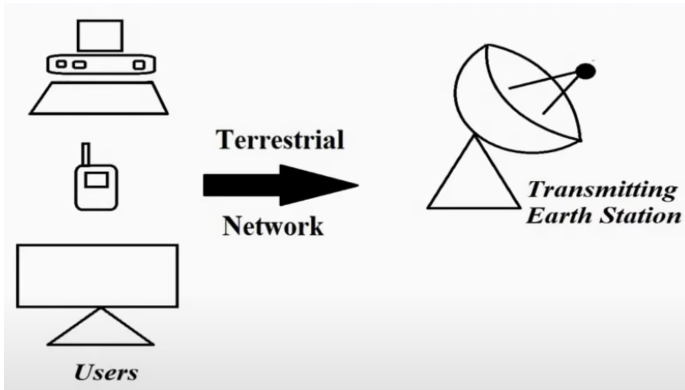

Figure 4: Flowchart of how terrestrial networks transfer data from the user to transmitting earth stations (*Basic Introduction To Satellite Communications*).

The last component of Satellite Communication is the user. The user, or person operating behind the device, provides the data for the entire process. The user is represented by whatever device is being used and linked to the satellite. The space segment is primarily only the satellite. There are many types of satellites that orbit at different levels such as geostationary satellites, low satellites, and medium satellites. The applications of these satellites heavily depends on the needs of the satellite and the distances that they are from Earth.

Transponders

Transponders are electronic devices that are typically used to receive, amplify, and retransmit signals. They operate within a specific frequency band given primarily for satellite communication and convert signals from one frequency band to another for efficient transmission and reception.

Steps Involved in Sending Data to Satellite

There are several steps involved in transmitting data to a satellite. These steps make it possible for the data to be received by the satellite. The first step is encoding the data. An encoder is used to change the data to bit sequences in order for machines to be able to understand the data. The next step is modulating the data. A modulator is used to change characteristics of the signal (phase, frequency, amplitude) in order to carry data. Then, an up converter is used in order to shift the signal to the uplink frequency from the downlink frequency. By using an upconverter, the band is converted from lower frequencies to higher frequencies and it is also amplified to make it more resistive to varying climate conditions, making it more likely to reach its final destination without interference. Then, the antenna sends the signal to the satellite and the process of sending the signal to the satellite is complete. See Fig. 5.

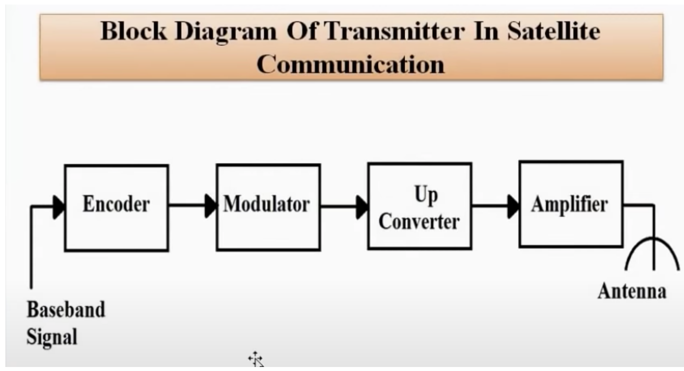

Figure 5: Diagram of Steps Involved in Transmitting Data to Satellite

Steps Involved in Sending Data to Ground Station

Similar steps apply to sending data to a ground station in comparison to sending data to a satellite. The first step in the process is the antenna receiving signal from the satellite. This is where the process of sending data upward ends and the process of sending data back downward begins. Then, an amplifier is used to amplify the signal because of the long distance that it has to travel. By doing this, it ensures that the signal will reach its final location undisrupted. Then, a downconverter is used to shift the signal back down to the downlink frequency range so that band is converted from upper frequencies to lower frequencies. After this, a demodulator is used to extract the original signal message from the modulated version and a decoder is used to convert the bitstream back to its original analog form. See Fig. 6.

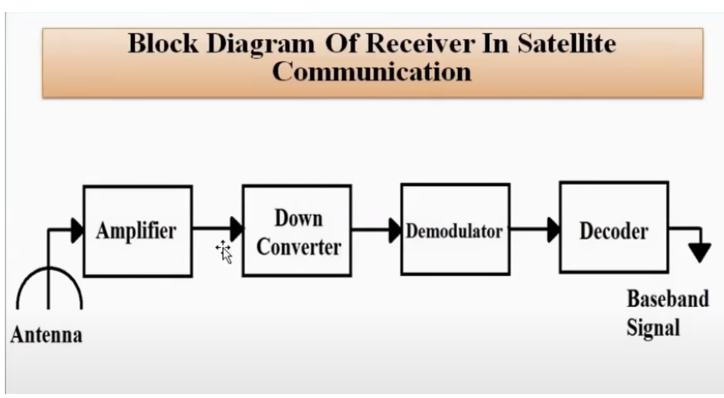

Figure 6: Steps Involved in Transmitting Data From Satellite to Ground Station

Overall, there isn't a large difference between the process required to send information from the ground station to the space system and from the space station to the ground station but there is one key difference and this is changing the uplink or downlink frequency. These steps allow for the transfer of information over long distances.

Areas of Development/Future Works

There is still much potential for new inventions in the field of satellite communications and wireless communication. As technology continues to advance, using satellites for data transmission will become continuously more important because of their utility and efficiency.

Autonomous Cars

Right now, many large technology companies such as Tesla and Rivian are working on creating autonomous cars (Goncharov 2023). Autonomous cars are cars that have the ability to drive themselves, they are typically referred to as self-driving cars. Autonomous cars are beneficial because they have the ability to prevent crashes that are created by common human errors such as distracted or drunk driving (Steinger). An example of this is if someone was driving home after a night out and had too much to drink. It would be illegal and dangerous to drive home alone but if they had a self-driving car, they would be able to set the location they were driving to and not have to worry about driving. This technology has the potential to prevent many accidents that are caused by intoxicated and distracted driving as well as driver error.

Satellite Communications Applied to Autonomous Cars

Satellite communication based technologies are being used to help enhance and increase the capabilities of autonomous cars. Without the input of the driver, they have no sense of direction, leading self-driving vehicles to rely on satellite based navigation systems in order to function and transport passengers from one place to another. The Global Positioning System (GPS) is used to determine the exact location of the vehicle and use it in order to navigate from the first point to the next. GPS satellites then continually transmits signals with time and location information which the vehicle receives using its GPS receiver. This is called real-time data exchange. Earth observation satellites are used to receive information about road conditions, traffic patterns, weather, and anything else current or important. A signal containing all this information is received by the vehicle and then processed and used to calculate the speed, direction, and current location of the vehicle. This allows the vehicle to make decisions on how to travel to the desired location. Satellites are the reason that autonomous vehicles are able to function because without them, there wouldn't be technology that allowed for fast transfer of information from various points to the vehicle. Without this information relay, routing and decision making wouldn't be possible.

Limitations with Navigation Technology

Though using satellites for navigation and routing is efficient, there are also a few disadvantages. The biggest drawback is satellite signal interference. Satellites operate by sending radio signals in order to transmit data to ground stations and nterference from tall structures, like mountains or buildings, or weather conditions can disrupt and weaken the signal. This is the main limitation because in urban areas, there are many tall buildings that could disrupt the signal. Another limitation to using satellites for navigation is lack of coverage in remote areas. In some remote or less populated areas, satellite coverage can be limited or unavailable. Because of this, if a passenger was to live or venture through these areas, it wouldn't be convenient for them to use autonomous vehicles because their GPS may be unavailable and the vehicle wouldn't be receiving any data from satellites to guide the trip.

Addressing Limitations

Addressing signal interference is difficult because it is a flaw within systems that isn't easily fixable. However, some researchers and engineers are working on creating more sophisticated signal processing algorithms in order to lessen the effects of interference and improve the accuracy of GPS. Some of these techniques include filtering noise and amplifying weak signals. To address the issue of lack of coverage in remote areas, some companies are using Low Earth Orbit (LEO) satellite networks. These satellites are smaller and orbit closer to Earth making them better for communication. Because there are also many more of these in comparison to regular satellites, they provide people in remote areas with satellite coverage and internet connection (Schafer).

Conclusion

Signal processing is a field that has been important in technology for many years. Through using signals and systems, we are able to transmit data globally as well as analyze and optimize it. There are many fields of technology that rely on signals and systems. In the future, signal processing will continue to be prominent in many technologies as wireless communication technology continues to improve. Hopefully, we will continue to learn more about this field and soon also be able to apply it to autonomous vehicles.

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