Sure-Fi Technology Whitepaper

Rev 7

March 1st 2019

I. Sure-Fi Communication Technology Overview

Overview

Sure-Fi communication technology is best suited for those applications that require extremely high reliability and low data rates. It might be the most reliable commercial communications technology available today. The technology platform has at its core Chirp Spread Spectrum which utilizes chirp pulses for the transmission of each symbol of data. A chirp pulse is a sinusoidal signal whose frequency increases (or decreases) linearly over the duration of the pulse. A single symbol of data is spread over the entire bandwidth of the chirp pulse making it robust to channel noise. The symbol size, the chirp bandwidth, and the spreading rate (based on Spreading Factor), are all configurable making the technology scalable. In addition to chirp spreading, the technology also utilizes frequency hop spread spectrum signaling to further enhance the robustness to channel noise. The overall effectiveness is seen in the technology's performance in non-line-of-sight environments where the communications link is relegated to only multipath signals with no direct signal path to rely on.

Industry Demand for High Throughput

In the field of wireless communications there seems to have always been a greater emphasis on the development of products and communications infrastructures that focus on the highest data rates possible which has in turn left a gap in the market for products like Sure-Fi. Not only has this trend been true for wireless digital telephony and associated 2G, 3G, 4G, and now 5G standards for mobile phone networking, but also nearly every other form of wireless communications. Wi-Fi (IEEE 802.11b/g/n) has evolved from approximately 10Mbps to 1Gbps to handle the increasing data demand of the internet and video-on-demand. Bluetooth, 802.15.1 started with 1Mbps data rates and has evolved to 3Mbps per channel (2.0+EDR, Enhanced Data Rate). Zigbee, 802.15.4, has focused more on low data rate applications but has a defined data rate of 250Kbps which is still a relatively high throughput for low data intensive operations (i.e. turning things on and off). Each of these examples operate at 2.4Ghz or 5.8Ghz to provide the highest data rate possible for their specific class of application. In contrast, the Sure-Fi radio module has focused on data rates in the 300bps to 10kbps range to allow for maximum range and reliability.

Extreme Connectivity

Because of the limitations of ISM (license free) bands and because the emphasis in major markets has been focused on maximizing throughput, there is a glaring deficiency in wireless communications systems available today for extreme connectivity or what we will call “mission critical” or reliable communication. We have all learned to accept dropped calls, pauses in streamed movies, dead spots for Wi-Fi, and so on, but there are applications that really need reliable, basic communications for which Sure-Fi was developed. Several examples of mission critical applications are: fire alarms, access control to buildings for fire or police departments, refrigeration to avoid expensive losses, tank level controls to avoid caustic spills, and HVAC controls in assisted living facilities. All of these areas could benefit from the use of Sure-Fi technology.

Wire replacement

The option most needed and most overlooked for reliable wireless communications is a wire replacement technology. Any technology capable of replacing wire and performing reliably will need to have the capability of connecting not just in non-line-of-sight (NLOS) environments but with a large number and variety of obstacles between the transmitter and the receiver, what we will call an extreme NLOS environment. This environment is a challenge to any wireless technology and has an associated trade-off of reducing the available bandwidth for reliability. It is tempting for the wireless development community to tackle this problem by adapting existing technologies and adding mesh networking capability, but this also has the cost of adding delays, reducing throughput, and adding system complexity which not only adds risks to connectivity but fails to take into account that not all obstacles can be circumvented.

Non-Line-Of-Sight Environments

While Sure-Fi communications modules can connect at great LOS distances, Non-LOS environments are the primary target for the Sure-Fi technology because these environments are underserved by wireless technologies of the day. Until now, wired connections were really the only high reliability solution for commercial buildings and other situations with numerous obstacles including metal, brick, concrete, pipes, and similar materials scattered about. Examples of environments suitable for Sure-Fi technology are: Small to medium sized campuses (building to building), factories and production sites, large industrial buildings, office buildings, hi-rise buildings, apartment buildings, correctional facilities, large assisted living centers, or combinations of such environments.

II. Sure-Fi Communication Technology Description

Sure-Fi Technology

So why is Sure-Fi Chirp based wireless technology able to operate in extreme non-LOS environments? The underlying technology is Chirp Spread Spectrum Communications (Chirp Modulation). A chirp symbol or pulse is a sinusoidal signal whose frequency increases or decreases over time. When the frequency increases it is called an upchirp and when it decreases it is called a downchirp. Figure 2 shows a time domain diagram of a chirp pulse whose frequency increases linearly from f1 to f2. The difference between these two frequencies is the bandwidth B of the chirp pulse (or symbol). Multiple chirp pulses are chained together to make up a data packet consisting of multiple preamble chirp pules for determining timing, and multiple data chirp pulses for communicating data. However, the high robustness of CSS communications comes from the properties of the individual pulses and the fact that there are a relatively small number of them. Each pulse, which sweeps the transmitted bandwidth, is encoded (modulated) with a single symbol of information. Each symbol (the smallest unit of information transmitted over the air) is spread over this entire bandwidth. This, along with the mathematical properties of a chirp not only make it extremely robust but easy to process.

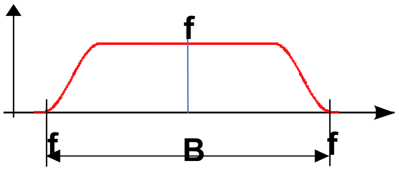


Figure 1

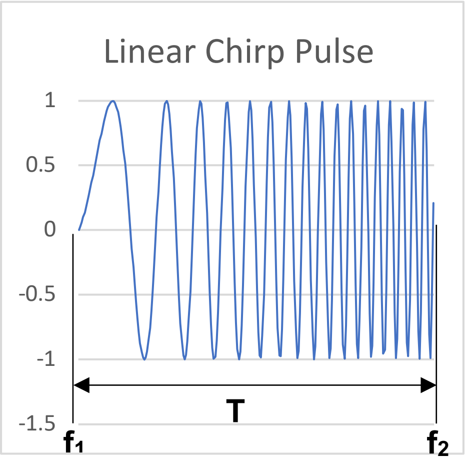
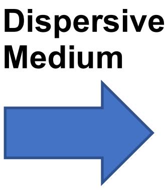


Figure 2



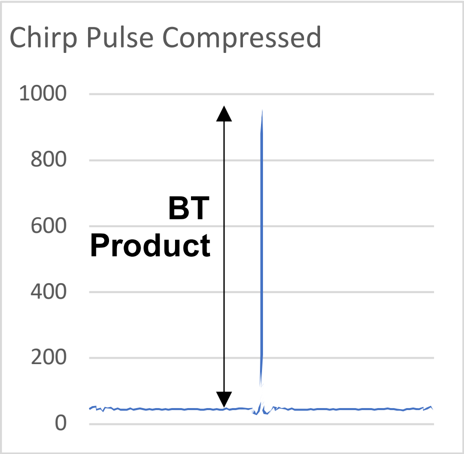


Figure 3

Chirp Symbol Processing

Each transmitted chirp consists of 2^{SF} (the chipping rate) number of incrementing frequencies which are generated by a lookup table and input to a Numerically Controlled Oscillator (NCO). The same NCO can be reused by the receiver to generate a conjugate chirp used to multiply against each of the received chirp chips (clocks). This product is stored and run through a Fast Fourier Transform (FFT) processor. When a received preamble or data chirp is found in the product, one of the FFT bins will be significantly larger in value than any other. The specific bin number will correlate directly to the TX/RX timing offset for a preamble chirp and will correlate directly to a data value for a data chirp (a form of pulse position modulation). The number in the largest bin corresponds with the BT product which also corresponds to the energy of the chirp pulse. It is due to the high BT product (>>1) that makes CSS robust.

Time Bandwidth Product

Chirp pulses are unique due to high spectral energy/density which makes it very robust and resistant to multipath, noise and other impairments. It is commonly expressed that this robustness is due to the high time-bandwidth product, or BT, but it is not usually explained. It can be somewhat confusing because BT as a figure of merit for spread spectrum communication systems is usually thought of as smaller than 1 and is inversely proportional to spreading rate (processing gain). For chirp pulses BT is much larger than 1 and directly proportional to spreading rate (compression ratio).

> In a sense, while not precisely accurate, one could think of chirped modulation BT as the number of frequencies per bit and for standard modulation as a number of bits per frequency, which kind of illustrates the odd inverse relationship of their BT.
>
> Because chirp signals have a large time-bandwidth product (BT) during transmitting in the channel, both the signal and noise spread on the wideband. But at the receiver, the signal produces a pulse peak due to its autocorrelation (matched filter detect) while the noise is further spread and has rather small amplitude. This also contributes to better immunity to jamming, (narrowband) noise, and multipath impairments.
>
> Its autocorrelation has a time duration of 1/B. The higher its time-bandwidth product, the higher the statistical precision in recovering the signal preamble or data and the higher the amount of energy present inside the defined chirp.

Frequency Hopping

Frequency Hopping (FH) is another form of spread spectrum to be combined with chirp spread spectrum to further enhance the performance of the Sure-Fi communication technology. The technology utilizes “Slow Frequency Hopping” for addition immunity to noise and to add multiple access capability. The base technology utilizes 72 pseudorandom, table driven frequencies which are scalable to adapt to any regional requirement worldwide, or to adapt to symbol bandwidths. Proprietary algorithms are implemented for table synchronization and adaptation for minimizing frequency dwell time performance per regional regulatory requirements. The technique is internally referred to as “Spectrum Impact Smoothing”.

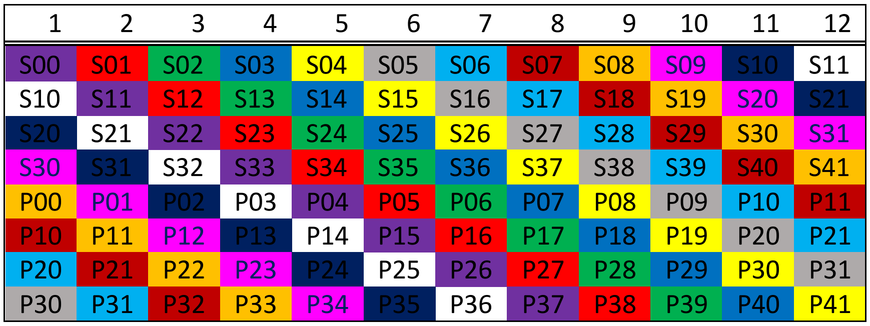
Forward Error Correction

All data packet transmissions include Forward Error Correction (FEC) based on Hamming (8,4) coding which allows for a single bit correction per transmitted data word, further enhancing data link performance by improving coding gain. Hamming FEC is notoriously efficient from an implementation viewpoint which is consistent with the low latency, fast acquisition, low cost features of the technology.

Data Interleaving

The technology link performance is further enhanced by the incorporation of diagonal interleaving combined with FEC for burst error immunity. Referring to Table 1, assume that Sxx is data and Pxx is parity:

- data is assembled for transmission in columns 1 through 12, and data is reassembled in columns 1 through 12 after reception but sent over-the-air in order of color with each column of 8 bits correctable for a single error.
- If any whole color is corrupted, representing an over-the-air burst of noise, all 12 columns could be recovered with a series of single bit error corrections.
- For varying packet sizes the table can be extrapolated to show 8 bits of burst error correction for every multiple of 8 bytes transmitted.



1	2	3	4	5	6	7	8	9	10	11	12
S00	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10	S11
S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21
S20	S21	S22	S23	S24	S25	S26	S27	S28	S29	S30	S31
S30	S31	S32	S33	S34	S35	S36	S37	S38	S39	S40	S41
P00	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11
P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21
P20	P21	P22	P23	P24	P25	P26	P27	P28	P29	P30	P31
P30	P31	P32	P33	P34	P35	P36	P37	P38	P39	P40	P41

Table 1

Security

The technology incorporates an AES 128 cryptographic algorithm for all over-the-air data packets, which includes a proprietary over-the-air rekeying process for key distribution and other information obscuring techniques. Data security is an important topic covering both real and perceived liabilities whether related to banking systems or critical controls, vulnerable to vandalism. It makes intuitive sense that RF communication systems would potentially be vulnerable and need security, but what is not as intuitive is that a new or retrofit system solution could increase security where little or none exists in the industry, especially wire replacement technologies. Data security is one of the many benefits that Sure-Fi provides.

III. Advantages of Chirp Based Spread Spectrum

Local Oscillator Precision

It is well known and documented that CSS systems have an advantage in that they require far less local oscillator (receive and transmit clock) precision than do DSSS based systems, **5ppm vs 40ppm,** (parts per million) which is a **cost and hardware** advantage.

No Clock Synchronization

CSS receiver hardware requires no clock synchronization which is closely related to the local oscillator precision issue and is a somewhat foreign concept in the field of communications. This is due to the way in which the chirp preamble pulses are correlated (known as matched filtering, also known as pulse compression). The compressed pulses (markers, for lack of better terminology) of the preamble are nearly instantaneously mappable to the timing offset between the timing of the transmitter and the receiver symbol (chirp) timing. This means that the preamble (the first part of the over-the-air packet) doesn't need a clock training sequence and the receiver doesn't need a phase lock loop (PLL) or to spend the time to lock onto and recover the clock timing. This also minimizes the time required to cover the possible combinations of frequency and phase shifts a DSSS correlator requires and results in a **fast acquisition and low latency**.

High Robustness

Because of the high amount of spectral energy present inside a chirp pulse, as evidenced by a high time-bandwidth produce (BT), chirp spread spectrum communications is inherently immune to jamming, (narrowband) noise, multipath, and other impairments. Other spread spectrum technologies may claim a certain amount of immunity to such impairments, but none come even close to chirp spread spectrum performance.

Doppler Resistant

Doppler frequency shifts due to one radio moving relative to the other are relatively insignificant in chirp technology. The overall effect of Doppler is a small shift in the time axis of the received baseband signal. Since the over the air packet is relatively small, the preamble and the data portion of the packet will see the same shift which will automatically be cancelled by the normal receive processing which makes this technology inherently useable in mobile applications.

Scalable Technology

The modulation scheme is both frequency and bandwidth scalable. The Spreading Factor (SF) which determines the number of chips per chirp symbol can be easily be reconfigured as well as the bandwidth occupied by the chirp symbol, even on the fly. These factors are typically chosen from a trade-off between robustness and data bandwidth for given applications. Also, the bandwidth size and number of hopping frequencies are easily configurable which not only helps with efficient use of the allocated frequency band, after adapting to various modulations schemes, but makes it relatively easy to adapt to regional frequency regulations around the world.

Frequency Hopping

Chirp modulation is inherently easily adapted to incorporate frequency hopping spreading in addition to the chirp spreading. This is due to both the packet format/size and the rapid acquisition process mentioned above.

Chirp Multiplexing

Inherent to chirp modulation is the ability to multiplex packet transmissions not only based on the time of the chirp, but also based on the properties of the chirp such as rate of frequency change, and phase. The Spreading Factors (SF) mentioned above can be and are chosen such that they are orthogonal to each other. This means that multiple chirp bursts with different SFs can be transmitted simultaneously on the same frequency and received simultaneously, where the receivers are tuned to the specific SF, without colliding or needing to be retransmitted. Each receiver "matched filter" will only detect the burst to which it is tuned based on SF. This not only creates an opportunity for multiple access to aid in networking but also for different node types to operate adjacently without congesting the RF space.

Low Out of Band Emissions

Out of band emissions are generally desirable not only to help create an efficient network design and allow for the efficient use of sub-frequencies (i.e. hopping frequencies), but also to help with the testing and qualification of the hardware for regional regulations. While good design practices play a role, this technology is inherently efficient with respect to "out of band emissions".

IV. RF Communication Systems Background Information

Impairments to RF Signal Propagation

Frequency Flooding

The existence of license free frequency bands, such as Industrial Scientific Medical bands (ISM), at 400Mhz, 800Mhz, 900Mhz, 2.4Ghz, and 5.8Ghz, depending on regional requirements, has led a certain amount of overlap between users particularly in congested areas such as apartment buildings, businesses, stadiums and similar situations. This overlap can lead to collisions and slowdowns or even lack of connectivity altogether and is referred to a frequency flooding. This is particularly true where multiple standards use the same frequencies such as Wi-Fi and Bluetooth, and where standards and companies are pushing the limits of power and range. Bluetooth, for example, was originally designed for close personal usage such as wearable devices, keyboards, and similar, requiring short range but is now finding applications requiring much longer ranges and finding more diverse uses. The Internet of things (IoT), which is essentially the concept of expanding the internet into nearly every space and thing, is making frequency overlap even worse. 2.4Ghz tends to be a very popular frequency and is therefore more likely to be flooded depending on location but the problem occurs on or near many frequency bands including licensed bands such as used by cell phones such as GSM-900, GSM-1900. Additionally, harmonic effects potentially cause signals from one frequency band to contaminate other frequency bands.

Properties of Frequencies

The general trend throughout the world is to accommodate as much throughput as possible connecting more and more multimedia devices. This tends to drive developers to higher frequencies because the higher frequency bands allocate higher bandwidth. However, there is a penalty for this trend in that the higher the frequency the less it will penetrate objects, as a rule. Therefore, the *lower frequency bands tend to be more robust*. The choice of a carrier frequency can help in mitigating impairments.

Distance

All line of sight (LOS) RF communication signals will diminish in power density as a function of distance through space which is referred to as path loss. Power density follows an inverse square law, $P= 1/d^{2,}$ which is to say that power density is proportional to the inverse square of the distance. This law is based on the geometry of a point-source radiation into 3D space.

Physical Obstructions

All low power RF communications, particularly at frequencies above 30Mhz, (such as license free ISM band frequencies) are impaired to varying degrees by obstructions in the geometric line of sight between the communicating device antennas. These obstructions can be trees, landscapes, buildings, objects, heavy rain or snow, etc. Nearby objects can also disturb line of sight signal propagation even if they don't block the geometric line between antennas due to multiple reflections (multipath fading) of the of the RF signal alone the path. These reflected signals can recombine (misaligned) with the line of sight signal causing it to be impaired or faded. These impairments are known as multipath fades. In an extremely impaired environment, such as with many objects and no line of sight, multipath signals are seen as distributed and referred to as *Rayleigh Fades*.

Methods of Mitigating Impairments to RF Signal Propagation

Spread Spectrum Modulation

This is technique used for transmitting an RF signal whereby the over the air bandwidth is much greater than the bandwidth of the original information. Spread Spectrum communications can be thought of as a signal structuring technique that minimizes the effect of interferers (over the air) but that has a penalty of decreasing the data throughput of the link.

> **Direct Sequence** – This is a modulation technique whereby each data bit, of a stream to be transmitted, is combined with a large number of random Chips whose sequence is known (pseudo noise code), resulting in large redundancy per bit (the spreading ratio = chips/bit). This helps to increase the signal's resistance to interference. If any bits are damaged during transmission, the original data can be recovered due to the redundancy of transmission.
>
> **Frequency Hopping** – This is a modulation technique whereby each over the air data packet is transmitted on a different frequency chosen from a pseudo random list known to the transmitter and the receiver. If a particular frequency is not suitable as a carrier due to multipath interferers it can be temporarily or permanently skipped. While the spreading ratio is Number of frequencies per data bit, it can be thought of as more efficient when considering sharing between transmitters
>
> **Chirp** – This is a modulation technique whereby a wideband linear frequency modulated chirp pulse is used to modulate data. A chirp is a sinusoidal signal whose frequency increases or decreases over time. When a chirp's frequency increases it is called an upchirp and when it decreases it is called a downchirp.

Forward Error Correction

This is a digital signal processing technique used to enhance data reliability over an unreliable or noisy communications channel by adding redundancy to the data, error correcting code (parity). This allows the receiver to detect and correct a certain number of errors without the need to retransmit the message.

Interleaving

When combined with Forward Error Correction, data interleaving is a cleaver technique whereby the ability to correct for one or more bits errors per word is improved to many bit errors, for burst protection, simply by the way in which the data is ordered over-the-air.

Process Gain

Process gain is a measurement of improvement (signal-to-interference) due to frequency spreading and is defined as the ratio of spread (RF) bandwidth to the un-spread (or baseband) bandwidth.

Code Gain

Code gain is the measure of Signal to Noise Ratio (SNR) improvement introduced by coding such as Hamming FEC.

Performance Comparison between Spectrum Systems

Chirp Based Spread Spectrum vs Direct Sequence Spread Spectrum

One might ask the question, how does this technology compare to other premier spread spectrum technologies of our day, such as Direct Sequence Spread Spectrum (DSSS)? DSSS is a high-end signaling technique used by well know systems such as the Global Positioning Satellite (GPS) system, Common Data Link (control link for Predator unmanned aircraft), as well as numerous commercial systems such as cordless telephones. There are also numerous chip suppliers who supply inexpensive DSSS chips such as Analog Devices Inc. (ADI), Cypress Inc, and others. One might presuppose that a particular spreading ratio of one technology would accomplish a similar robustness as the same spreading ratio of another technology and to a certain extent would be correct. For example, multiple studies have been made to compare Chirp Spread Spectrum (CSS) to Direct Sequence Spread Spectrum (DSSS) through modeling. It was found that CSS and DSSS performed similarly with Rician fading models, which is what one would find in a typical line-of-sight (LOS) scenario with objects along the LOS path. But when Rayleigh interference models were used, which best fits environments with severe obstacles in a Non-Line-Of-Sight scenario in which the dominant signal is a multipath signal, CSS significantly outperformed DSSS. One might keep in mind that the CSS technology used in these studies did not include other enhancements of the Sure-Fi technology such as combining CSS with Frequency Hopping which is also a spreading technology and enhances link performance.

Rician Fading Performance

A Rician fading model is a stochastic model for radio propagation anomaly caused by partial cancellation of the radio signal itself due to interference from multiple reflections of the signal. This model is useful for modeling communications systems when the transmitted signal can travel to the receiver along a dominant line-of-sight or direct path. The Rician model could be made to fit a scenario typified by the propagation of a signal along a road with reflections from the road or from objects along the path such as trees and buildings or other urban interferences.

Rayleigh Fading Performance

A Rayleigh fading model is also a stochastic model for radio propagation but is used where the wireless channel varies randomly and has a heavy build-up effects from urban RF interferers with no dominant propagation signal, as is true when there is no geometric line-of-sight. This model could be made to fit a scenario typified by the propagation of a signal within a factory with brick, metal, or concrete barriers between the transmitter and receiver and clutter throughout the area.

Spread Spectrum Figures of Merit

Time-Bandwidth Product

Time-bandwidth product of a pulse is the product of its temporal duration (T in figure 2) and spectral width in frequency space (B in figure 1) and is usually lower bounded and highlights the uncertainty principle that both the duration and the bandwidth of a signal cannot be made arbitrarily small simultaneously. For standard modulation waveforms this lower limit indicates how close the pulse duration is to the limit which is set by its spectral width and indirectly related to the number of chips per bit or spreading rate. However, chirped pulses have a relatively "ultra-wide" bandwidth and large time-bandwidth product BT and the interesting property that it does not depend on the symbol rate, theoretically a single bit (or symbol) per chirp.

License Free Frequencies

ISM band Carrier Frequency

Radio frequency allocations were made prior to the advent of most of the wireless communication devices we use today such that there really weren't actual license-free frequency allocations for these devices. Instead, non-licensed frequencies were allocated to the anticipated and non-anticipated Industrial, Medical, or Scientific (ISM) uses. The possibility of microwave ovens was just on the horizon so 2.45Ghz was included in the list of frequencies established by the International Telecommunications Conference of the ITU in 1947. As a result, most of the common wireless devices today are non-ISM uses of ISM bands which is why so much technology and cleverness goes into the design of these devices to maximize throughput and range given the restrictions of bandwidth and transmit power.

900Mhz Carrier Frequencies

900Mhz carrier frequencies are a favored choice of carrier for many robust communication systems and are chosen from the most applicable non-licensed ISM band frequencies for the region 902Mhz and 928Mhz for the US and Canada. These bands offer two advantages, 1) 900Mhz penetrates obstacles better than do higher frequencies (2.4Ghz- 5.8Ghz), and 2) it is less flooded with contentious transmissions.

V. Chirp Signal Robustness Illustrated

Matched Filter Detection of chirp Pulses

One can easily see the properties of the chirp pulse by observing a simulated output of the “matched filter” (detection peak) within the CSS receive processor given various conditions. Note that simulations are baseband only and exclude RF considerations. The conditions include: 1) Attenuation of the chirp amplitude , 2) Addition of a tone jamming signal within the chirp frequency band, 3) Addition of various delays of the chirp representing multipath, and 4) Blocking noise in the form of a tone within the band but not added to the chirp. Figure 4 shows the “matched filter” output with the input chirp significantly attenuated simulating fading due to distance (reference point). Note that this value was chosen to allow signal to noise ratio (SNR) to be a significantly large negative number (i.e. the signal is buried in the noise) simultaneous with normal fading. Figure 5 shows the addition of 1 multipath signal (50% amplitude of the main chirp) delayed by 12.5% of chirp time T. Figure 6 shows the addition of 2 more multipath signals (50% amplitude of the main chirp) delayed by 25% and by 50% respectively. Note that no matter how many multipath signals are present the main detection peak is preserved in the simulation even while numerous multipath signals are present. The correlator will correctly choose the main peak even when it is prevalent only by a few counts. This illustrates a high level of immunity to multipath and how a dominant peak is not necessary, which is unlike any other spread spectrum topology. Figure 7 shows the addition of a jamming tone to the chirp with an SNR of at least -10dB. Figure 8 shows the addition of the same jamming tone but as blocking noise. Figure 9 shows the addition of a jamming tone to the chirp while the keeping the previous 3 multipath inputs of Figure 6. Figure 10 shows the addition of a jamming tone to the chirp plus the blocking noise while the keeping the previous 3 multipath inputs of Figure 6. Notice that the main detection peak is preserved in the simulation regardless of the chosen impairments and it is evident in the simulations how noise is further spread rather than being matched by the correlator. Also, notice that the main detection peak is not only preserved with the addition of noise and multipath interference but potentially improved. In the final example the detection peak improved from ~48.5 to ~60 counts. This is unlike any other spread spectrum topology known and provides a glimpse into chirp spread spectrum link performance in the presence of impairments.

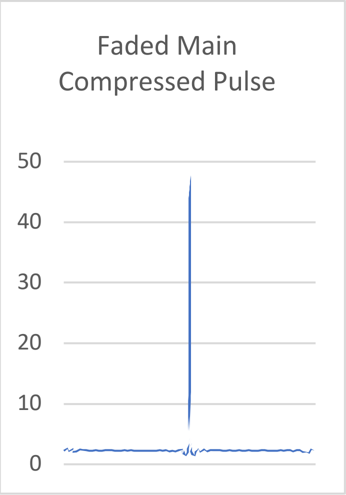


Figure 4

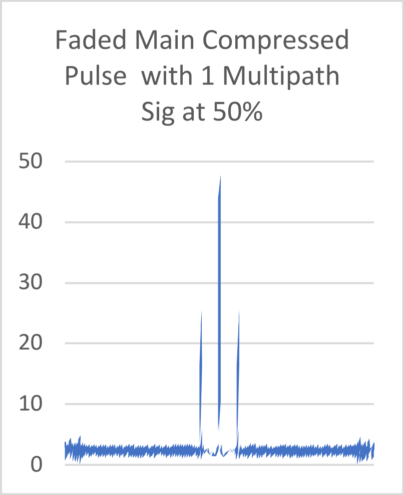


Figure 5

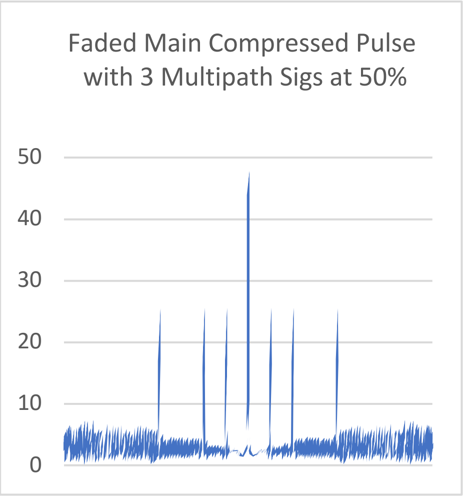


Figure 6

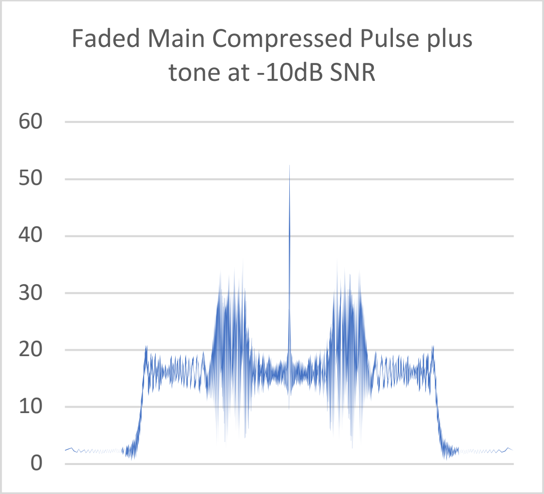

Faded Main Compressed Pulse plus tone at -10dB SNR

Figure 7

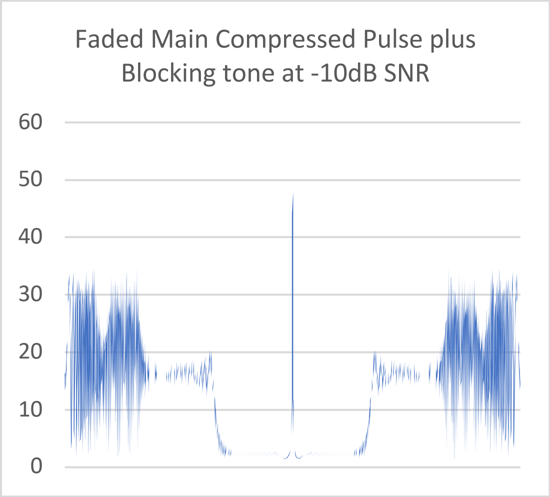

Faded Main Compressed Pulse plus Blocking tone at -10dB SNR

Figure 8

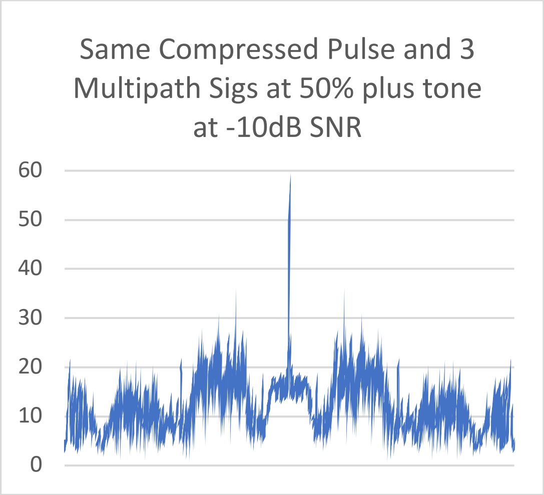

Same Compressed Pulse and 3 Multipath Sigs at 50% plus tone at -10dB SNR

Figure 9

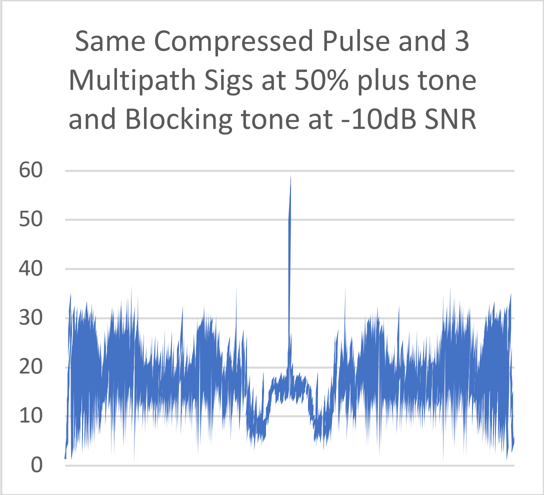

Same Compressed Pulse and 3 Multipath Sigs at 50% plus tone and Blocking tone at -10dB SNR

Figure 10