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High-speed Track-and-Hold Amplifiers in CMOS for Enabling Pulse-based Directional Modulation, Secure Communication and Precision Localization

by

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Abstract

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Last few decades have seen a puissant desire for fast communication links that has shaped the evolution of high-speed circuits and silicon-based technology. This desire accompanied with a large consumer market has fueled the development of ever-shrinking, faster technology nodes. These advanced nodes open doors for designers to develop new ways of transferring data with unprecedented speed and accuracy.

There are a number of challenges in building high-speed, secure communication links, one being the lack of availability of fast Analog to Digital Converters (ADCs), which form the front end of a receiver. Even in advanced technology nodes, the leakage in the transmission gate due to parasitic source-drain capacitance provides an alternate path for signals to pass, thus lowering the performance of the ADCs at high frequencies. Second, the current communication schemes use beam-forming or Direct Antenna Modulation (DAM) to narrow the information beam and point it in the direction of communication. Such techniques still have a wide information beam compared pulse-based directional modulation, as discussed in this thesis.

In this dissertation, we address the issue of parasitic leakages in the
transmission gate of a fast sampler by introducing active cancellation. A track-and-hold amplifier with active cancellation is designed and fabricated in 45nm CMOS SOI technology, which can operate at 40GSample/second real-time. In addition to this, we also study a pulse-based directional modulation scheme which can be used for secure communication, imaging and localization. Two coherent pulse generators with pulse width less than 200ps were used to attain an information beamwidth of less than 1° and localize objects with millimeter accuracy.
ACKNOWLEDGEMENTS

During my graduate studies at Rice, I have had the chance to meet some of the best and brightest minds from all around the world. The most important lesson that I have learnt is to be humble and hungry. Be hungry for knowledge in the most humble way.

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To My Parents & Khushboo.
“Speak only if it improves upon the silence.” —Mahatma Gandhi
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Introduction

Limited bandwidth and security have become paramount concerns in the ever-growing digitally connected world. The current wireless communication channels have reached their maximum Shannon capacity, and researches are investigating higher frequency to cope with the demand. However, moving to higher frequencies limits the transmitted range and makes the electronics expensive. On the other hand, various beamforming [1] and directional modulation [2] techniques are being implemented to make the communication link more directional and secure. However, such schemes need additional transmitting/receiving elements with added hardware and a large computational back-end. In addition to this, these systems are very narrow-band and with limited bandwidth.

In this thesis, we will explore the possibility of using pulse-based systems for communication and localization. An in-depth characterization and performance evaluation is done. Finally, a high-speed, wide-band track-and-hold sampling core is designed, fabricated and tested, which can be used as a core of an ADC block for on-chip implementation of such pulse based systems.
1.1 Motivation

The following section presents the motive to solve the problems faced in this thesis at an intuitive level. A compendious technical motivation appertaining to each problem is provided in the chapter.

1.1.1 Pulse-Based Communication and Localization

Current communication and localization systems are build around continuous wave (CW) architecture. Such architecture operate in a very narrow frequency range, which limits its bandwidth and speed. Moreover, in continuous wave communication systems, the transceiver uses a large train of repetitive signals in order to identify a constellation point which makes the system slower and less energy efficient \[3\]. In addition to this, multi-path reflections can considerably hinder the performance of such systems \[4\]. This is due to the fact that most CW systems operate in a frequency domain and do not use time domain information to filter the reflections.

A time domain pulse-based system architecture is introduced that mitigates/eliminates some of the inherent drawbacks of CW systems. It uses time domain pulses for communication and localization. Being a pulse-based architecture, the system is ultra wide-band and uses a single pulse for each transmitted symbol. Moreover, the ability to coherently combine the pulses at a specific point adds a layer of spatial encryption and power combining, which is difficult in CW architecture. In future chapters, we will explore the advantages and performance gain of pulse-based architecture.

1.1.2 Development of High-Speed, Wide-Band ADC

In order to make an on-chip pulse-based communication and localization system, it’s very important to have an ultra wide-band high-speed ADC core around which
the receivers can be built. With the latest advancement in technology nodes, the operational speed of electronics circuits rises as the size of transistors becomes even smaller. However, a decrease in size increases the parasitic leakage current, which decreases the effective number of bits.

A new track-and-hold architecture with active cancellation is proposed that takes advantage of the latest technology node for high speed while mitigating the parasitic leaking using active cancellation. A detailed analysis of this architecture is explained in future chapters.

1.2 Layout of Thesis

The remainder of this thesis is divided into three independent chapters followed by a concluding statement. Chapter 2 proposes a broadband time-domain pulse-based directional antenna modulation architecture to substantially increase the security of wireless communication. Chapter 3 propose a novel technique for improving the accuracy of localization and the resolution of imaging radars using a time-domain pulse-based directional modulation. In Chapter 4, a new architecture for high-speed track-and-hold amplifier with active cancellation is presented that will form the core of ADCs used in future on-chip receivers.
2.1 Pulse-Based Secure Communication

Conventional wireless communication links consist of a transmitter and a receiver, whose directivity is predominately defined by the radiation pattern of the antenna. A problem of security in such conventional systems arises due to the wide pattern beam width of the transmitting antennas. Any sensitive receiver, even the ones outside the main lobe of the radiation, can receive and decode the information, making the system spatially insecure. Near Field Directional Modulation (NFDAM) systems \cite{2,5} modulate the signal at the antenna level to make the information beamwidth narrow and directional, without narrowing the radiation pattern. NFDAM (or directional modulation) transmitters scramble the signal constellation points outside the main information beamwidth, thus preventing even a sensitive receiver from decoding the signal outside the information beamwidth. Most of the prior work on directional modulation focused on narrow-band continuous-wave transmitters \cite{2,5}.

In this paper, a broadband time-domain pulse-based directional antenna modulation architecture is introduced that can substantially increase the security of wireless communication. In the proposed architecture, multiple widely spaced transmitting
antennas are synchronized at the symbol level to generate a very narrow (∼1°) information beamwidth.

### 2.1.1 Proposed Idea

The proposed idea uses Amplitude Modulation (AM) to establish communication using short pulses. In contrast to conventional wireless communication systems, where the complete constellation symbol is transmitted from one antenna (in case of phased array, from all antennas), the proposed idea fundamentally differs in the topology. Instead of sending the complete constellation symbol (complete information) from a single antenna, a part of the symbol (semi-symbol), which is a fraction of the total amplitude, is sent from one antenna and the remaining fraction is sent from other antennas. The transmitting antennas are synchronized at the symbol level. A receiver that is placed exactly at the point where all the semi-symbols arrive at the same time sees the correct complete symbol. The point where all the semi-symbols combine coherently is unique in space, and being so, the communication can be said to be spatially encrypted.

The proposed idea is explained with two transmitters. Let $S_{\text{orig}}(t)$ be the signal that corresponds to a complete symbol. This signal is divided into two overlapping

---

**Figure 2.1: Antenna Setup**
semi-symbols, $S_1(t)$ and $S_2(t)$, such that $S_{\text{orig}}(t) = S_1(t) + S_2(t)$. These two signals $S_1(t)$ and $S_2(t)$ are generated at Tx$_1$ and Tx$_2$, respectively, using two synchronized base-band waveform generators. Assuming there is a separation of D between Tx$_1$ and Tx$_2$, the signal received at different angles in space will be $S_1(t-\tau_1) + S_2(t-\tau_2)$, where $\tau_1$ and $\tau_2$ are the propagation delays from Tx$_1$ and Tx$_2$ to a point, P, in space, respectively. As shown in Fig. 2.1, if point P is located equidistance from Tx$_1$ and Tx$_2$, both the signals will reach at the same time and will overlap/coincide with each other, thus generating the desired signal/symbol. However, if $\tau_1 \neq \tau_2$, the received signal will be $S_1(t-\tau_1) + S_2(t-\tau_2)$, which is distorted and non-overlapping as shown in Fig. 2.2.
2.1.2 Working Explained

For the sake of simplicity and without loosing any generality, two transmitters (Tx\textsubscript{1} and Tx\textsubscript{2}) and one receiver (Rx) are chosen. The two transmitters are synchronized time-domain short pulse generators with amplitude modulation capability. The transmitters have 10 steps of amplitude modulation (e.g. 0.1, 0.2 ... 0.9, 1.0). For simplicity, only the first 2-bits (four levels) of modulation are used (from 0.1 – 0.4). Thus, each transmitter can transmit 2 bit amplitude-modulated synchronized Gaussian pulses (semi-symbols). The received signal for an equidistant receiver will be the sum of the transmitted signals (semi-symbols) whose amplitude corresponds to a certain bit value.

From here on, bit values are assigned to corresponding received amplitudes. For instance, a received signal with peak-to-peak voltage of 0.3V will be referred to as bit ‘00’, 0.4V as bit ‘01’ and so on and so forth, as shown in Table 2.1.

For instance, if Tx\textsubscript{1} transmits semi-symbol X\textsubscript{1} and Tx\textsubscript{2} transmits semi-symbol X\textsubscript{2}, the received signal will be the sum of transmitted signals, X\textsubscript{1} + X\textsubscript{2}. For two different transmitted semi-symbols, the received symbol will be the same as long as their sum is constant and the receiver is equidistant from both the transmitters. However, in the case when the receiver is not equidistant, there will be no or partial overlapping of the semi-symbols, which will distort the received symbol. This distorted symbol will have a different peak-to-peak amplitude than the sum of two semi-symbols. This incorrect amplitude will correspond to a different bit, and thus be read erroneously by the eavesdropper. Moreover, with the possibilities of assigning different semi-symbols for the same transmitted symbol, the statistical symbol recovery for the eavesdropper becomes even more difficult. This could be further understood from Fig. 2.2.

Table 2.1 tabulates all the possible combinations of transmitted and received symbols for an equidistant receiver antenna.
Figure 2.3: Pulse Combining in Air
<table>
<thead>
<tr>
<th></th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tx1 (Semi-symbol)</strong></td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Tx2 (Semi-symbol)</strong></td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Tx1+Tx2 (Complete-symbol) [Bits]</strong></td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: Transmission Table for Transmitter

### 2.1.2.1 Division algorithm

The semi-symbols for each transmitter are generated based on the final symbol to be sent. For instance, if bit “10” is to be sent, the transmitters randomly chooses one of the four possible semi-symbol combination as shown in Table 2.1.

### 2.1.2.2 Receiver decoding algorithm

The receiver is in the line-of-sight (LOS) with the transmitters. It uses the amplitude of the combined signals to detect different symbols. A look-up table is used to convert the detected amplitude to bits. The generation of this table is discussed in Section 2.1.4.

### 2.1.2.3 Beam steering capability

It’s important to note that even though the results are discussed for an equidistant receiver, the desired focus point of the system can be changed by introducing proper relative delays in the transmitters. These delays will determine point in space where the semi-symbol combines correctly, providing the lowest Bit Error Rate (BER) during communication. Thus, one of the advantages of this topology is the convenience of changing the direction of information beam by introducing relative delays in the transmitters.
2.1.3 Experimental Setup

The experimental setup consists of an arbitrary waveform generator, which generates two streams of synchronized pulses. These pulses are amplified and transmitted using impulse antennas designed to operate in the 3–10 GHz band. A similar impulse antenna is used as a receiver. The received signal is amplified by an LNA before being sampled by a 25GS/s real-time oscilloscope. The two transmitters are placed at a distance of 0.6 m and the receiver antenna is placed at a distance of 1.2 m from a line connecting the two transmitters, as shown in Fig. 2.4. The cable length is carefully calibrated so that the pulses reach the transmitting antennas at the same time. The whole setup is automated using a Matlab code. In this setup, a master computer communicates with the instruments using GPIB-VISA protocol.

![Experimental Setup Diagram]

Figure 2.4: Experimental Setup

2.1.4 Setup Calibration and Table Generation

It is important to calibrate the system before performing the BER test. The system is calibrated by each transmitter sending all possible bits. Based on the received signal, the gain of the amplifier is recorded. The non-linearity in the gain of the amplifier is compensated by pre-distorting the input signal.

A look-up table is generated by sending random bits and recording the maximum
and minimum voltage levels for each symbol. For instance, the symbol corresponding to bit “00” (0.3 volts) is transmitted with all possible semi-symbol combinations. Even after performing the predistortion, for a desired symbol value of 0.3V, the receiver may receive a value between 0.28V to 0.31V, which is due to the non-linearity in the system. This level of error in the proposed architecture can be tolerated. The small deviation of received signal voltage over the original signal makes the system more robust and allows for improved BER performance. Finally, the thresholds are set midway between the symbol voltages and corresponding bits are assigned, as shown in Fig. 2.5.

![Figure 2.5: Transmission Look-up Table](image)

**2.1.5 Results**

To measure BER, a pseudo-random number generator is used to generate the transmitted bits. These bits are decomposed into symbols and symbols are then broken down into multiple pairs of semi-symbols. All these pairs of semi-symbols will generate the same complete symbol at the desired direction of transmission. A random generator picks one of these pairs and assigns it to two transmitting antennas. This random selection of the semi-symbol pair increases the complexity for the eavesdrop-
per to perform a statistical recovery. The received signal is then compared against the look-up table introduced earlier. Finally, the BER is calculated by comparing the received bits with the transmitted bits.

### 2.1.5.1 Time Domain Radiation Pattern of One vs Two Antennas

The radiation pattern of a single impulse antenna is derived by measuring the power of the radiated pulse as the function of angle, as shown in the Fig. 2.6. As expected, the radiation pattern of the single antenna is very broad. The power of the received pulse from two separate synchronized transmitting antennas is shown with dots. At the center, both the pulses overlap constructively, resulting in higher amplitude. However, as the receiver moves away from the center, the two pulses arrive at different times. The received pulse amplitude reaches a minima when the maxima of one transmitted pulse overlaps with the minima of another. This first occurs when the differential delay between the pulses is half the pulse width. Thus, by changing the pulse width, it is possible to change the location of the first null point.

![Figure 2.6: Effective Radiation Pattern](image-url)
2.1.5.2 Symbol Collapsing

As the receiver moves away from the center, one of the transmitted signals adds more delay. This differential delay causes partial symbol overlap. This partial overlap combined with the possibility of sending multiple semi-symbols for the same complete symbol results in a range of received amplitudes that overlaps with the amplitude of the other symbols (Fig. 2.5). This phenomenon results in higher BER for the receivers that are not located at the desired angle. The angular range between the two null points in Fig. 2.6 creates a void zone, near and beyond which the symbols cannot be distinguished, so the communication link cannot be established. Moreover, by reducing the pulse width, the void zone becomes smaller, resulting in a smaller information beam-width.

2.1.5.3 Radiation Pattern vs Information Pattern

An information pattern is used to represent the spatial information distribution of a communication system. Fig. 2.8 shows the BER of two synchronized pulse-transmitting antennas.

In this experiment, a BER of $10^{-2}$ at 1° and $10^{-6}$ at 0.47° were recorded. A linear extrapolation of these results gives a BER of less than $10^{-10}$ at the center.

An important observation to make is that the BER increases rapidly as the receiver moves away from the center. This phenomenon is caused due to symbol collapsing. In addition to this, a reduction in pulse width brings the null points in Fig. 2.6 closer to the center and symbol collapsing happens at a smaller angle. This effect enhances the security of the wireless link by making the BER well even sharper.
Figure 2.7: Measured Bit Error Rate
2.2 Pulse-Based Localization and Imaging

The ability to localize and image objects has always intrigued the scientific community. Such technology has proven to be of significant importance in the fields of security, air-traffic control, car anti-collision systems and more. Conventional RADAR systems rely on the echo of a continuous RF signal to determine the location and even the shape of reflecting object [6]. This approach has served the military and consumers for the past few decades [7, 8]. In this paper, we propose a novel technique for improving the accuracy of localization and the resolution of imaging radars using a time-domain pulse-based directional modulation.
2.2.1 Proposed Idea

In the proposed technique, a train of narrow time-domain pulses is used for localization and imaging. These pulses are generated, amplified and transmitted using impulse antennas. The radiated pulses get reflected from an object and are collected at the receiver. By calculating the time of flight (i.e. the time taken by the pulse to travel to the object, get reflected and come back), the total travel path distance can be calculated. A locus of points whose total distance from two points (transmitter and receiver) is constant forms an ellipse. Thus, a certain time of flight corresponds to a particular travel path distance. In order to triangulate the exact position of the object, more than one such ellipses are required as shown in Fig. 2.9.

![Figure 2.9: Triangulation using Time of Flight](image)

2.2.2 Experimental Setup

The block diagram of the experimental setup is shown in Fig. 2.10. A two-channel arbitrary waveform generator (Tektronix AWG7122C) is connected to the power amplifiers, each with 25dB gain, to generate the transmitted pulses. These generated signals are radiated using impulse antennas. A similar impulse antenna is used as a receiver whose signal is amplified by a 30dB gain LNA before being sampled by an oscilloscope. A copy of the original transmitted pulse signal is also recorded by the
oscilloscope to determine the time of flight. Care has been taken to make sure the lengths of the cable are equal, as the setup is sensitive to timing mismatch.

The distance between the transmitters is 940 mm and the receiver is placed in the middle but 150 mm behind the transmitters to reduce the direct coupling between the transmitters and the receiver.

![Experimental Setup](image)

Figure 2.10: Experimental Setup

The object to be localized is an acrylic rod, which is 12.5 mm in diameter. Since acrylic has a very weak RF signature, to make the object more reflective, a small stripe of aluminum foil, 10 mm in height, is wrapped around the rod in a way such that the middle of the stripe is at the same height as the center of the antennas. All acquisitions are automated using the MATLAB-toolbox and GPIB-VISA protocol.
2.2.3 Working Explained

The reflected Gaussian pulse that was radiated using the impulse antenna is recorded by an oscilloscope. A separate channel is used to digitize the copy of the transmitted signal. The recorded signals are downloaded from the oscilloscope to a computer over GPIB, where Matlab finds the peak in the reflected and transmitted signals to compute the time of flight. This time of flight information is then multiplied by the speed of light to give the round trip distance between the transmitter, object, and the receiver. Knowing the distance between the transmitter and the receiver, the desired ellipse can be drawn on which the object lies. Multiple transceiver pairs can be used to form multiple ellipses to triangulate the exact location of object(s). Fig. 2.11 shows the reflected signal and the time delay caused by the longer travel path. Fig. 2.12 shows the intersection of the ellipses to triangulate the location of the object.

2.2.4 Experiment Calibration

It is very important to calibrate the setup, as the experiments are extremely time and distance sensitive, so a two-stage calibration process is deployed.

During stage one, the cable lengths are adjusted in such a way that both the transmitted signals reached the antennas at the same time. Also, the delay in signal path from transmitter to antenna and antenna to receiver is carefully measured. These data are later used in distance estimation.

In stage two, ultra-shot pulses (~160ps peak to peak) are radiated using the impulse antennas. The object is removed from the scene (imaging arena) and the reflected signal is recorded. This captured time domain signal contains data about the background and its reflection signature. This signature is later subtracted from the reflected signal of the scene with the object present to increase the SNR of the system. Fig. 2.13 shows the reflected signal with and without the object. Fig.
2.2.5 Experimental Results

2.2.5.1 Single Object Localization

To validate the proposed architecture, various experiments were preformed to accurately determine the location/position of the object. This was done by placing an
The object on a one-dimensional travel table which can travel 300 mm with an accuracy of 0.01 mm. The rail was in alignment with the receiver antenna such that the object moved from 150 mm left of the receiver to 150 mm right of the receiver with steps of 10 mm, at a fixed perpendicular distance of 780 mm from the receiver antenna. Such an orientation was chosen because even though the object was moving in one-dimension, the total round trip distance changes parabolically, thus emulating two-dimensional motion. The dashed curve in Fig. 2.15 is the exact distance of the object from the receiver during the sweep. The dots represent the measured distance using the
proposed technique. It can be seen that the divergence of the measured distance over the actual distance is extremely small and that the variance is of the order of a few millimeters. Furthermore, from this time domain data, triangulation ellipses are drawn to calculate the absolute co-ordinates of the object. The exact and calculated X,Y co-ordinates of the object are shown in Fig. 2.16-17. Since the object is moving in X-direction, the X co-ordinates increases linearly while the Y co-ordinates stays
2.2.5.2 Multiple Object Localization

Multiple object imaging can be viewed as imaging discrete points. This assumption is valid if the objects are at a considerable distance from each other and do not obscure the RF signal. If such a pattern is followed, multiple ellipses can be drawn to triangulate the position of each point object. However, the above assumption is not always true and then imaging such a cluster is not trivial. Since the hardware limitation limits us to two transmitters and four real-time receivers, a mathematical model for imaging with multiple transmitter and receiver is build to extend the results of previous measurements. They are a part of further work.

2.3 Advantages of Pulse-Based Systems Over a Continuous Wave System

One of the major advantages of pulse-based systems over conventional continuous wave systems is the ability to mitigate the multi-path effect. In the case of pulse-based systems, the multi-path reflections will arrive at a different time, later than the one directly reflected from the object. Thus, its easier to eliminate such multi-path
reflected signals in time-domain based systems by discarding the signal that comes at a later time. However, in the case of continuous wave systems, the multi-path reflected signals interact with the line-of-sight reflected signal and changes the phase of the received signal, which is difficult to mitigate.

2.4 Novelty and Potential Applications

Proposed pulse-based communication system adds an extra level of security at the symbol level. This makes it extremely difficult for an evesdropper outside the information beam-width to unscramble the transmitted symbols. Such secure communication schemes are extremely useful in point-to-point, directional, high-data rate transmission channels. This scheme can be of significant importance in base-station to base-station links or in establishing secure communication between two military bases.

The RF-radar imaging has already shown its significance in automotive driving assistance and deep penetration imaging for aviation [9]. With the proposed imaging technique, we aim towards making pulse-based high-resolution radar systems that are less severely affected by multi-path effect and can attain higher resolution due to the smaller wavelength.

2.5 Conclusion

In this chapter, an ultra wide-band pulse-based directional modulation technique is introduced for secure communication and localization. An information beamwidth of $1^\circ$ is achieved using antennas with a broad radiation pattern. Moreover, localization with millimeter accuracy is demonstrated using sub-200ps pulses.
3.1 Introduction

The need for high-speed wireless and optical links are increasing every day and one of the bottlenecks is the availability of high-speed ADCs. These ADCs form the front end of almost every digital system. Several fields, from defense to communication to aviation, can all benefit from a faster ADC. Moreover, with the rise of pulse-based systems, a real-time high-speed ADC is a must in building an impulse receiver, such as the one mentioned in previous chapters.

Over the course of time, ADCs have evolved and many different topologies have been adapted from sample and hold to track and hold to master-slave configuration and many more, all with the objective to improve performance. Furthermore, to get a superior performance figure, designers have often focused on using InP or GaAs fabrication processes. These fabrication processes are expensive and increase the overall cost of equipment [10]. In my design, I introduce a novel track-and-hold (T/H) architecture with active cancellation, which is fabricated in IBM 45nm CMOS SOI technology [11].
3.2 Proposed Architecture

Sample and hold (S/H) or track and hold (T/H) amplifiers are used in the core of any ADC. These circuits sample the input signal and hold its value for a specific period of time. Traditional S/H or T/H circuits work well in low-input frequencies. However, as the input frequency increases, the isolation between the input and output of the T/H (or S/H) amplifier in the hold mode decreases, which reduces the effective number of bits. This is because the isolation of a CMOS switch degrades at high frequencies. In a series switch, the gate-source ($C_{GS}$) and gate-drain ($C_{GD}$) parasitic capacitors provides an alternate path for the signal to pass. This path causes a considerable amount of coupling at high frequencies and reduces the isolation. The low isolation changes the voltage of the holding capacitor in the hold mode and increases the error.

3.2.1 Active Cancellation

In the proposed architecture, an active cancellation circuitry is designed to maximize the isolation between the input signal and the holding capacitor in the hold mode. To achieve active cancellation, a negative copy of the input signal is generated on-chip using a single-ended to differential amplifier. The circuit diagram of the T/H amplifier with active cancellation is shown in Fig. 3.1. The single-ended RF signal is fed to a differential amplifier, which converts the input signal to a differential pair, one being the negative copy of the other. Ideally, this pair needs to have the same amplitude and $180^\circ$ phase difference in all frequencies. However, due to non-idealities caused by mismatches and process variations, large phase and amplitude imbalance may occur. To reduce these imbalance, the complementary pair is passed through a signal conditioning circuitry consisting of three consecutive differential amplifier and voltage follower stages.

After the signal conditioning block, the differential signals, which consists of the
Figure 3.1: The schematic of T/H circuit with active-cancellation.

Main signal and its negative copy, are passed through a T/H sampler with a differential input. A conventional T/H system consists of one transmission gate where the input signal is sampled. When the system is in the tracking state, the transmission gate conducts and charges the capacitor. During the hold state, the transmission gate changes to an isolation mode, and the capacitor holds the charge. However, due to the leakage of the transmission gate in the isolation mode, the charge in the holding capacitor changes, which increases the error and reduces the effective number of bits. In the proposed architecture, apart from the standard transmission gate, a second transmission gate is added, which is fed with the negative copy of the input. This added transmission gate is always in an “Off” state or isolation mode. During the hold state, both transmission gates inject charges to the capacitor due to leakage; however, the charges injected are opposite in sign and cancel each other. This charge-canceling mechanism mitigates the leakage effect. This combined process can be seen as T/H with active cancellation. Finally, a high-input impedance buffer amplifies the voltage of the holding capacitor and feeds a 50Ω load.
3.2.2 Complementary Signal Generation and Conditioning

An active cancellation architecture needs the original input signal and its complementary copy. To generate the complementary signal, an on chip single ended to differential circuit is used. This circuit consists of a differential amplifier that converts the single-ended input signal to differential output. The differential output signal has a large phase and amplitude imbalance. In order to reduce this imbalance over a wide range of frequencies, the differential signal is passed through a signal condition block. This block consists of multiple differential amplifiers in series with a voltage follower buffer to decouple subsequent stage loading. The high CMRR (Common Mode Rejection Ratio) of the differential amplifiers reduces the amplitude and phase imbalance of the differential signal. Fig. 3.2-3 shows the phase and gain imbalance after the final stage during simulations. In simulation, the 0.5dB amplitude imbalance occurred at 10GHz and a phase imbalance of less than 6 degrees at 10GHz.

![Figure 3.2: Complementary signal phase imbalance in simulation.](image-url)
Figure 3.3: Complementary signal gain imbalance in simulation.

3.2.3 Complementary Clock Generation and Sharpening

To operate the transmission switch, a clock (clk) and its complementary signal (clk') are required. A single ended 40GHz external clock is provided, which is converted into two complementary clocks with sub-10ps rise time. In this process, the clock is divided into two branches with one having an extra NOT gate to generate the complementary signal. Adding an extra NOT gate adds delay in one of the paths. This delay is compensated for by adjusting the number of transistors in one of the NOT gates. The fewer the number of transistors, the more time will it takes to drive the gate capacitance of the preceding NOT gate. Thus, by changing the number of transistors, the delay can be appropriately compensated. In simulation, the delay was compensated with picosecond accuracy.

3.2.4 Isolation Measurement in Simulation

Active cancellation circuitry increases the isolation during the hold mode by mitigating the parasitic leakage of the transmission gate. To measure the effectiveness of the system, the transmitted power through the system is measured in track mode.
Then the sampler is switched to the hold mode without active cancellation and the transmitted power is measured again. As shown in the fig. 3.4. the isolation quickly drops as the the input frequency increases due to leakage. Next, the active cancellation block is activated and measurement is done. There is an increase in isolation by more than 30dB at 10GHz, which shows the effectiveness of the active cancellation. Furthermore, the results are validated with experimental measurements.

![Isolation measurement in simulation with and without active cancellation.](image)

**Figure 3.4: Isolation measurement in simulation with and without active cancellation.**

### 3.3 Measurement Results

The T/H circuit with active cancellation is characterized using 67GHz RF probes and a two-channel 70GHz sampling oscilloscope (Agilent DCA-X 86100D). The RF signal generator and the sampling clock are synchronized using a 10MHz reference signal as shown in Fig. 3.5.

In order to characterize the performance of the active cancellation block, the isolation of the transmission gate in the hold state should be measured. To measure this
isolation, first, the spectrum of the output signal is recorded in the tracking mode. This should characterize the amplifiers and all other blocks in the signal path. Next, the state is changed to the hold mode, and the output spectrum is recorded again. The difference between the results of the first and second experiments is used to calculate the isolation. The input frequency is swept from 100MHz to 10GHz and the isolation is measured as shown in Fig. 3.6. Based on this measurement, an isolation of better than 32dB is achieved at 1GHz.

In a separate measurement, to characterize the Spurious-Free Dynamic Range (SFDR) of the sampling block, an input signal with a frequency of 1GHz was sampled at frequencies 5GHz to 30GHz. This measurement was made by calculating a
Figure 3.6: Measured isolation by comparing the track and hold modes.

30-point DFT of 1GHz signal, sampled at 30GS/s over a period of 1ns, averaged 128 times to reduce the noise of the oscilloscope. These points were taken in the middle of the hold state in the sampled waveform with constant repetition rate. The time-domain waveform of the sampled signal is shown in Fig. 3.7.

Fig. 3.8 shows the second and third harmonic Spurious-Free Dynamic Range (SFDR2 and SFDR3) for the system using different sampling rates. The hold-state SFDRn denotes the ratio of the fundamental frequency magnitude over the n\textsuperscript{th} harmonic spurious magnitude. As evident from Fig. 3.8, 68dB SFDR3 and 67dB SFDR2 were observed for 1GHz signal sampled at 30GS/s. Moreover, the SFDRn versus the input signal power is measured to demonstrate the linearity of the T/H amplifier. As evident from Fig. 3.9, 62dB SFDR3 and 55dB SFDR2 are observed for 5GHz signal sampled at 40GS/s.
Figure 3.7: Measured time domain waveform of a 1GHz input signal with real time sampling frequency of 30GS/s.

The results of this chip are compared with the prior art in Table 3.1.

<table>
<thead>
<tr>
<th>IC Specifications</th>
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<th>[13]</th>
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<td>4V, 3.3V</td>
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<td>SFDR=42dBc@Tone=30GHz, Fs=40GS/s</td>
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<tr>
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<td>&gt;55dB@ Fin=5GHz, Fs=40GS/s</td>
<td>SFDR=40dB@ Fin=3GHz, Fs=30GS/s</td>
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<td>Not reported</td>
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<td>Droop Voltage</td>
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<td>10 mV/ns</td>
<td>Not reported</td>
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Table 3.1: Comparison Table with Prior Art.

3.3.1 Droop voltage

Droop voltage refers to the decay of charged capacitor under the loading of following stage buffer circuit. Traditionally for high-input frequency samplers, a smaller
sampling capacitor is used to keep the RC constant small. But small capacitors can change its voltage very quickly with a small charge injection. In samplers without active cancellation, the parasitic leakages inject large amount of charge during the hold mode which considerably changes the voltage of the small capacitor. To reduce this effect, large holding capacitors are used, which reduces the overall system performance. With the introduction of active cancellation, the parasitic charge injection is considerably reduced in the hold mode, thus allowing designers to use smaller holding capacitors, which in turn improves the overall performance of the sampler. Experimentally, a droop voltage of 20\(\mu\)v/ns was observed for a sampled signal of 350mV. This is equivalent to 10-bit accuracy for a hold time of 10ns.

Finally, the chip micrograph is shown in Fig. 3.10. The chip is fabricated in 45nm SOI technology and occupies an area of 850\(\mu\)m\(\times\)450\(\mu\)m including pads.
Figure 3.9: Measured SFDR2 and SFDR3 versus input signal power at sampling frequency 40GS/s.

Figure 3.10: Chip micrograph in 45nm.

3.4 Acknowledgment

The authors acknowledges the help of Mr. Rafael Puhl in the measurements. They also acknowledge DARPA for fabrication support.
In this dissertation, the design and fabrication of a novel high-speed track-and-hold sampler with active cancellation is presented along with a proof of concept for pulse-based directional modulation, which can be used for secure communication and precision localization.

Conventional samplers use a transmission gate as a switch to sample the signal. This switch should ideally provide infinite impedance when in the “off” mode, but at high input frequencies, the isolation is low due to parasitic leakages. The parasitic source-drain capacitance provides an alternate path for the charge to flow, thus reducing the isolation in the “off” mode. We have introduced the concept of active cancellation in ADCs. An extra transmission gate is added in parallel to the original transmission gate, fed by a complementary signal and the original signal, respectively. The added transmission gate injects a charge, almost equal but opposite in nature to cancel the charge leakage from the original transmission gate. Thus, by introducing active cancellation, the isolation between the track mode and the hold mode can be increased, even at higher input frequencies.

A 40GS/s track-and-hold amplifier is designed and fabricated in 45nm CMOS technology, which uses active cancellation to reduce the parasitic leakage and increase
the performance. The measurement results were published at the International Microwave Symposium (IMS) 2014 and was chosen as a runners-up to the best paper award[11].

We also study and evaluate the concept of pulse-based directional modulation. In this proof of concept, two or more synchronized pulse transmitters use coherent combining of pulses for secure communication and localization. For secure communication, a train of short pulses are transmitted from multiple synchronized transmitters. These pulses coherently combine at a particular point in space. This point will receive the correct pulse amplitude that corresponds to a particular bit. All other points in space will receive scrambled pulse train amplitudes and thus result in high BER. The proposed scheme spatially encrypts the transmission at symbol level, making it extremely directional.

In addition to secure communication, directional modulation of pulses can be used for imaging and localization. In our setup, time of flight information is used to localize the object in space. The current setup can be expanded to multiple transmitters and receivers for more precise localization and even 3D imaging.

As mentioned in the introduction, the fast progress in developing process technologies funded by the worldwide consumer electronic market opens a new plethora of opportunities for RF/microwave designers doing research in the millimeter and sub-millimeter wave frequency range. These opportunities carry their own set of challenges which, if properly addressed, can open the door for the creation of revolutionary technologies.


