Behavioral Simulation Educational Framework for 2-Terminal MTJ-based Analog to Digital Converter

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***Abstract* - The emergence of advanced non-uniform Compressive Sensing (CS) signal processing techniques and spin-based devices has led to the development of novel Analog to Digital Converter (ADC) architectures. Herein, a novel interactive simulation framework is developed to provide widespread access to the ADC architecture designed using commercially-available 2-terminal Magnetic Tunneling Junction (MTJ) devices. The proposed ADC simulation framework utilizes CS techniques to provide insights for educational and technical purposes. The proposed framework provides simulation results spanning from the energy consumption required by each sample and MTJ device to the switching behavior of each MTJ device. Additionally, the results demonstrate the type of signal used along with the bias voltage required to switch each MTJ device. However, currently, 2-terminal MTJ devices and advanced signal processing techniques are not part of the Electrical and Computer Engineering undergraduate curriculum. To mitigate this challenge, the proposed framework has an educational resource site companion to distribute the interactive tool and further provide insights into the modeled Spin-based ADC by showcasing the research it was based on. Finally, the educational resources site also includes video tutorials to further engage the students and teach undergraduates the fundamental behavior of MTJ devices and utilization of the interactive simulation framework.**

Index Terms - Educational Resources, Emerging Devices in STEM Curricula, Magnetic Tunnel Junction (MTJ), Spin-based ADC.

INTRODUCTION

With the commercialization of beyond Complementary Metal Oxide Semiconductor (beyond-CMOS) computing devices, new tools and techniques to realize efficient and reliable circuits that use them and extend previous validated circuit resilience approaches are sought [1-9]. Spin-Transfer-Torque based Magnetic Tunnel Junctions (STT-MTJs), have been recently commercialized after being explored by researchers for many years. STT-MTJs are suitable for applications such as nonvolatile memory due to their near-zero power consumption, area efficiency, and fast read operation [7]. STT-MTJs contribute valuable properties such as non-volatility and stochasticity, allowing them to be suitable for diverse applications [1-3,7]. Still, STT-MTJs suffer from higher energy of the write operation compared to their CMOS-based counterparts due to ohmic loss and joule heating during switching [1]. Finally, MTJ devices facilitate the usage of advanced non-uniform CS and signal processing techniques on novel signal acquisition hardware platforms which provides a lower energy consumption on sampling operations.

Although commercially-available, currently, 2-terminal STT-MTJ devices and their innovative applications such as in Analog-to-Digital (ADC) architectures are not widely-integrated into the educational curriculum of many Electrical and Computer Engineering undergraduate programs. Viable educational approaches and simulation-based systems are helpful to explain the operation of electronic devices and their application via hands-on activities, often integrating teaching with recent research approaches [11-15]. Our proposed approach is an on-going effort to develop an interactive simulation framework that students are able to manipulate to generate different simulation scenarios by modifying the parameters of 2-terminal spin-based devices. Thus, a bridge is developed and made available to provide online resources for these new emerging devices. Besides these web-based tools, chatbot-style interfaces that support conducive interactions [17-18] are a longer-term outcome worth pursuing, while providing an Intelligent Tutoring System backend to guide the learning process [19]. Ideally, the online resources will be interactive so that students can extend the electrical fundamentals that they already know using the emerging devices and a constructive approach examining the behaviors graphically from any location without the need for purchasing any software.

Herein, we propose an interactive simulation framework that can aid students in learning advanced STEM-related concepts in the field of emerging devices and signal processing. The proposed interactive simulation framework presents users with customizable parameters to showcase the adaptive behavior of spin-based ADCs. Undergraduate students can utilize the tool to familiarize themselves with 2-terminal MTJ devices by simulating different scenarios on a previous spin-based ADC design found on [1]. Moreover, an interactive educational resource site that maintains student engagement by distributing the interactive simulation framework and providing tutorials that aid students into further their understanding of MTJ devices and usage of the interactive simulation tool. Furthermore, the interactive simulation framework aids in the exposure of advanced topics in STEM-related fields which can attract undergraduate students into graduate school.

The remainder of the paper is structured as follows. A general background information on 2-terminal STT-MTJ and spin-based ADC designs are provided on Section II. An overview of the simulation framework composed of a spin-based ADC interactive simulator tool and an education resources site along with simulation results is provided on Section III. Finally, Section IV concludes the paper.

Background

A. 2-terminal STT-MTJ

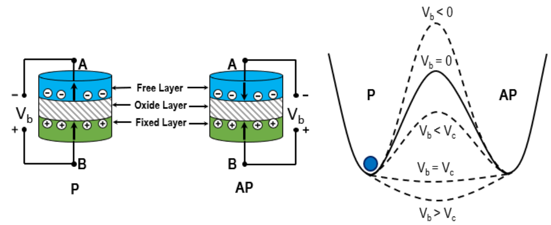
Recent research has shown, that utilizing a magneto-electrical field instead of current change for MTJ device manipulation, can reduce energy by modification of the switching energy barrier. This proposed solution helps mitigate the high dynamic power consumption caused by current-driven operations [1,6]. This magneto-electric field effect, called Voltage Controlled Magnetic Anisotropy (VCMA) effect, can benefit MTJ devices by providing fast efficient switching while also providing less overall energy consumption. The VCMA effect utilizes an electric field which causes a change in the energy barrier by storing electron charges that results in a deterministic change of the MTJ. The structure of the VCMA-MTJ device is composed of two Ferromagnetic (FM) layers and one tunneling oxide layer located between the two FM layers, called fixed-layer and free-layer respectively. The structure features two different magnetization states called Parallel (P) and Anti-Parallel (AP) which determines the switching state of the MTJ device. VCMA-MTJ devices require a bias voltage being apply through its terminals for switching between P and AP which allows for low magnitude currents and short pulse durations to switch the orientation of the MTJ devices. The equations used for the modeling the VCMA-MTJ device are as follows [1,6]:

$$K_{eff}(V_b) = \frac{M_s H_{eff}(V_b)}{2} = \frac{K_i(0) - K_i(V_b)}{t_f} - 2\pi M_s^2,$$

where V_b is the voltage being applied by the VCMA effect, M_s is the saturation magnetization, $K_i(0)$ is the initial joint Perpendicular Magnetic Anisotropy (PMA) energy, $K_i(V_b)$ is the joint PMA energy under the application of the bias voltage, t_f is the free-layer thickness of the MTJ, $H_{eff}(V_b)$ is effective magnetic field under the application of the bias voltage, and $K_{eff}(V_b)$ is the effective PMA,

$$\Delta(V_b) = \frac{E_b(V_b)}{k_B T} = \Delta(0) - K_i(V_b)\frac{A}{k_B T},$$

where A is the sectional area of the MTJ, k_B is the Boltzmann constant, T is the temperature, $\Delta(0)$ is the initial thermal stability factor at zero voltage, $E_b(V_b)$ is the voltage-driven energy barrier, and $\Delta(V_b)$ is the thermal stability factor at bias voltage, and



(a) (b)

Figure 1: (a) VCMA-MTJ Structure, and (b) Energy barrier modification using VCMA Effect [1].

$$V_c = \Delta(0)\frac{k_B T t_{ox}}{A\xi},$$

where t_{ox} is the oxide layer thickness of the MTJ, ξ is the VCMA coefficient, and V_c is the critical voltage required by the VCMA effect to change the state of the energy barrier.

Since VCMA-MTJ devices utilizes a bias voltage to change the state of the device due to energy barrier manipulation, this effect results into fast and energy efficient write operations. Based on equation (3), we can calculate the value for the bias voltage to modify the state of the VCMA-MTJ device. The VCMA effect can be modeled using a modified version of the Landau-Lifshitz-Gilbert (LLG) equation in which the following equations are derived from [1, 6]:

$$\frac{d\vec{m}}{dt} = -\gamma\vec{m}\times\vec{H}_{eff}(V_b) + \alpha\vec{m}\times\frac{d\vec{m}}{dt} - \rho_{stt}\vec{m}\times(\vec{m}\times\vec{m}_r),$$

where $\vec{m}_r$ is the polarization vector, $\vec{m}$ is the MTJ's free-layer magnetization vector, ρ_{stt} is the STT factor, α is the Gilbert damping factor, and γ is the gyromagnetic ratio,

$$\vec{H}_{eff}(V_b) = \vec{H}_{ext} + \vec{H}_{dem} + \vec{H}_{th} + \vec{H}_{ani}(V_b),$$

where $\vec{H}_{ani}(V_b)$ is the voltage-driven anisotropy field vector, $\vec{H}_{th}$ is the thermal noise field vector, $\vec{H}_{dem}$ is the demagnetization field vector, and $\vec{H}_{ext}$ is the external magnetic field vector, and

$$\vec{H}_{ani}(V_b) = \frac{2K_i(0)t_{ox} - 2\xi V_b}{\mu_0 t_f M_s t_{ox}} m_z,$$

where μ_0 is the vacuum permeability and m_z is the magnetization orientation of the free-layer of the MTJ in the z-axis of the Cartesian coordinate system. Based on above equations, there is a continuous change present and utilized by the VCMA effect as the voltage-driven anisotropy field is modified using a bias voltage. This results in the utilization of lower magnitude currents at faster switching rates because of lower energy barriers caused by the VCMA bias voltage. This means that under writing operations, MTJ devices will now possess a significant reduction in energy consumption compared to the previous switching mechanism such as Spin Transfer Torque (STT). Utilizing a positive bias voltage causes the magnetic coercivity present in MTJ devices to decrease via PMA reduction whereas a negative bias voltage causes the magnetic coercivity to increase via PMA

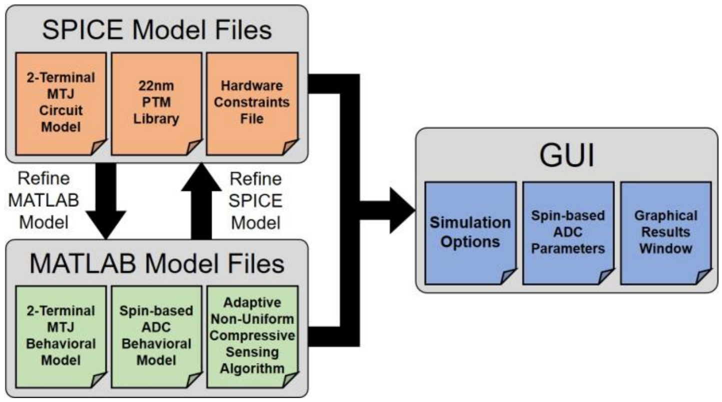


Figure 3: Interactive Simulation Framework developed for undergraduate instruction.

enlargement [1]. The structure of and the VCMA effect on MTJ devices can be seen in Figure 1.

B. Spin-based ADC Design

Recent studies exploit the usage of spin-based devices for adaptive signal acquisition [1-3], and advanced non-uniform sampling techniques such as Compressive Sensing (CS) [1,2]. Since CS measures the information rate rather than the Nyquist rate of sparse signals, it allows for computationally-efficient acquisition of spectrally sparse wide-band signals. CS implementations, along with spin-based devices, can further optimize the energy consumption of the overall sampling [2]. The integration of spin-based devices with CS techniques into novel Analog-to-Digital Converters (ADC) designs allows for adaptive sampling rates and quantization resolutions during signal acquisitions and offers a wide range of accuracy, bandwidth, miniaturization, and energy trade-offs compared to their non-CS counterparts. However, CS techniques mostly do not consider the hardware constraints that can affect the sampling and reconstruction performance, which is addressed in [1] in the form of an Adaptive Intermittent Quantizer (AIQ).

The proposed AIQ design, shown in Figure 2, utilizes both spin-based devices and CS techniques to perform at fast Sampling Rates (SR) while providing adaptive Quantization Resolutions (QR) [1]. AIQ is composed of 2-terminal MTJ devices that utilizes the VCMA effect which allows for energy efficient sampling and acquiring operations. By utilizing the VCMA effect, AIQ provides different quantization levels in the form of Q, shown in Figure 2, which determines the number of bits being used by the ADC for adaptive efficient signal acquisition. The 3-step operation of the AIQ includes: 1) a reset step in which the magnetization state of all 2-terminal MTJ devices are set to Parallel state or zero, 2) a sampling step in which first, a bias voltage is applied to adjust the energy barrier of the MTJ devices and second, an analog input, e(t), is applied to change the magnetic state of the MTJ devices, and 3) a sensing step in which a sense amplifier is used to read the values stored in the MTJ devices.

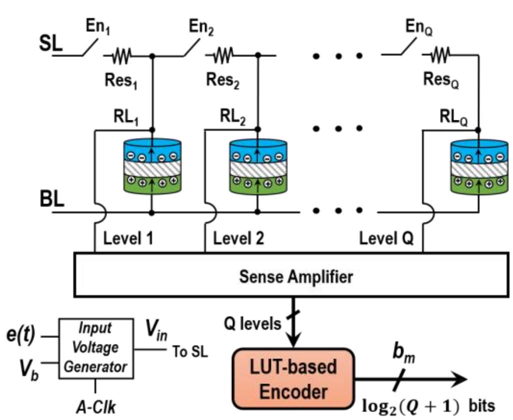


Figure 2: AIQ Architecture proposed in [1].

ADC is a commonly covered topic in the undergraduate curriculum. Thus, we have devised an interactive simulation framework to implement the aforementioned AIQ design proposed in [1] to enable the users to design and run simulations to validate their results.

PROPOSED SIMULATION FRAMEWORK

A. Spin-based ADC Interactive Simulator

Herein, an interactive simulation framework is proposed which enables the users to get familiar with the mechanisms of the Spin-ADC. The proposed framework allow users to setup simulation and MTJ parameter values and perform the simulation utilizing a Graphical User Interface (GUI). Figure 3 depicts the modeling process of the proposed Spin-based ADC simulation framework and GUI. Additionally, Figure 4 illustrates the GUI designed for the proposed simulation framework. Default parameter values reflect simulation cases used in [1]. Additionally, device parameters can be modified for performing different simulation runs considering various scenarios. Moreover, the ***Run*** option compiles all parameters and simulation options to prepare and display the simulation results in form of visualized graphs. For each simulation run, the results are displayed in a separate GUI window. Figure 5 and Figure 6 depict sample output shown for two separate simulation runs using the proposed framework. Furthermore, we have provided a ***Help*** menu that redirects the users to our educational resources site for more information regarding the proposed framework.

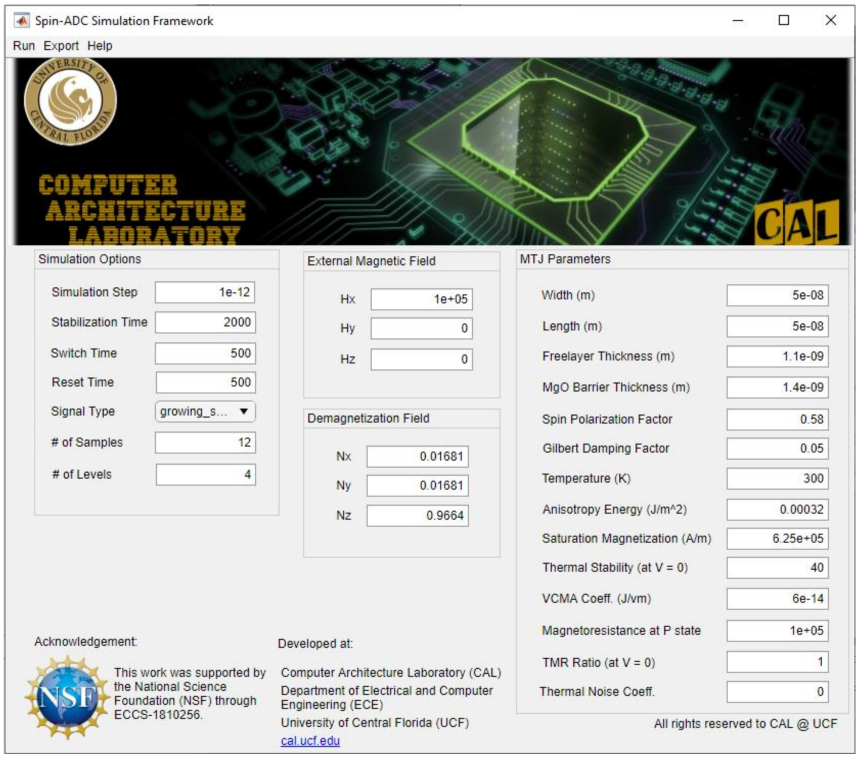


Figure 4: Spin-based ADC Interactive Simulation GUI.

In particular, Spin-ADC Interactive simulator is divided into two main components. The first component is the model developed using both SPICE and MATLAB for the AIQ design utilizing the equations provided in Section II-A [1]. The second component is a main GUI that is divided into four different panels. As shown in Figure 4, the main GUI is composed of the simulation panel, MTJ parameters panel, the external magnetic field panel and the demagnetization field panel. Simulation panel offers control over the type of signal being used, number of levels and samples, and the run time of the simulation. The MTJ parameters panel offers a comprehensive list of variables that can be manipulated to adjust the behavior of the 2-terminal MTJ devices. The external magnetic field panel and the demagnetization field panel allow for the control of the magnetization dynamics of the MTJ devices. Default values for each field are presented in Table I, which are based on the information found in [1] and the equations discussed in Section II-A.

The main GUI also offers three functionalities: 1) ***Run*** option, 2) ***Export*** option, and 3) ***Help*** option. After inserting or modifying the values located on the GUI panels, the user is able to click on the ***Run*** option and perform a simulation using the set values for the parameters as input to the model of the AIQ design. Moreover, the acquired data from the simulation results can be further exported to a spreadsheet document using the ***Export*** option. Finally, the ***Help*** functionality redirects the user to our educational resource site to further explain in-depth features and functionalities of the interactive tool and more information on emerging devices. Furthermore, the main GUI illustrates the results in a separate window as shown in Figure 5 and Figure 6. Figure 5(a) and Figure 6(a) depict the energy consumption of each sample, Figure 5(b) and Figure 6(b) illustrate the energy consumed by each MTJ device, Figure 5(c) and Figure 6(c) demonstrate the magnetization orientation of each MTJ

TABLE I: Simulation Parameters with default values based on [1] for the 2-terminal MTJ device.

Parameter		***Description***	***Default Value***
GUI	***Equation***		
Width (m)	W	Width of MTJ	50*nm*
Length (m)	L	Length of MTJ	50*nm*
Free-layer Thickness (m)	t_f	Thickness of freelayer	1.1*nm*
MgO Barrier Thickness (m)	t_{ox}	Thickness of MgO barrier	1.4*nm*
Spin Polarization Factor	P	STT polarization factor	0.58
Gilbert Damping Factor	α	Gilbert Damping Factor	0.05
Temperature (K)	T	Temperature	300 *K*
Anisotropy Energy (J/m²)	$K_i(0)$	Initial interfacial PMA energy	0.32*m J/m²*
Saturation Magnetization (A/m)	M_s	Saturation Magnetization	0.625*M A/m*
Thermal Stability (at V_b = 0)	Δ(0)	Thermal Stability Factor at $V_b = 0$	40
VCMA Coeff (J/vm)	ξ	VCMA Coefficient	60*f J/Vm*
Magnetoresistance at P state	R_p	Magnetoresistance at parallel state	100KΩ
TMR Ratio (at V_b = 0)	TMR(0)	TMR ratio At $V_b = 0$	1
Thermal Noise Coefficient	Ψ	Thermal Noise Coefficient	0

TABLE II: Simulation setups with varying scenarios.

Simulation Runs	***Signal Type***	***SR***	***QR***	***Bit Budget (SR×QR)***
Run #1	Growing Sinusoidal	15	2 bits	30
Run #2	Ramp	10	3 bits	30

device, Figure 5(d) and Figure 6(d) show the analog input waveform and quantization levels, and Figure 5(e) and Figure 6(e) visualize sampling rate. Figure 5 and Figure 6 demonstrate different scenarios using different number of samples, number of levels, and signal types. The input values for each simulation result can be found in Table II considering a bit budget of 30. Additionally, *mz(i)* shown in Figure 5(c) and Figure 6(c), illustrates the magnetization orientation of the MTJ devices where *i* represents the MTJ device number.

B. Educational Resources Site

The educational resources site focuses on explaining the purpose of the interactive tool and possesses two main functionalities. First, to easily distribute and disseminate the proposed interactive tool herein in the form of a download option as an executable .mcr file. This way the users do not

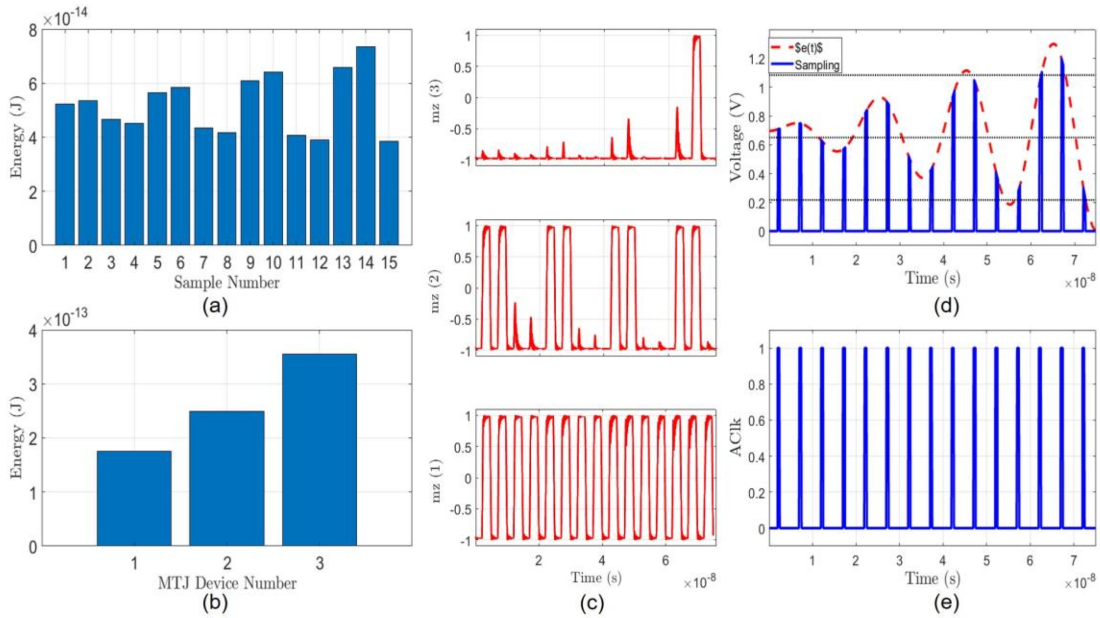


Figure 5: Simulation Run #1 using Input Signal= Growing Sinusoidal, SR=15 Samples, and QR=2 Bits.

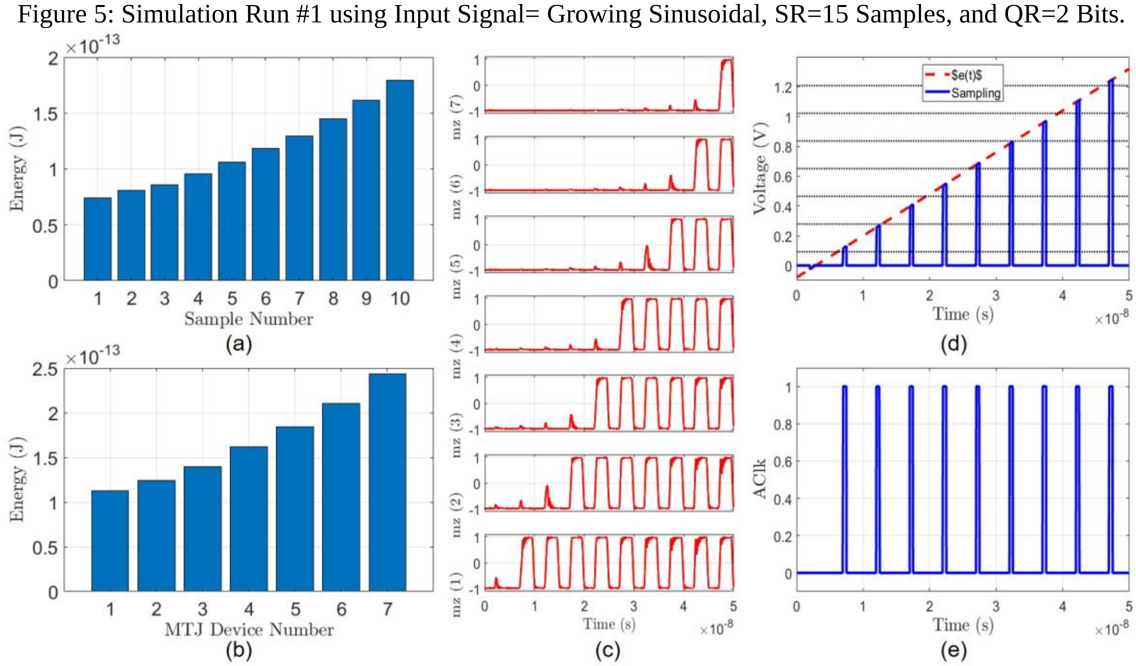


Figure 6: Simulation Run #2 using Input Signal= Ramp, SR=10 Samples, and QR=3 Bits.

require any external or additional installation other than the tool's setup installation. Second, to explain different functionalities of the developed simulation framework and walkthroughs using YouTube video tutorials. To disseminate the use of the interactive tool, there are YouTube video tutorials that inform users on how to interact with the simulation framework and explain the different parameters that can be modified by users. Additionally, the website contains the research papers that helped develop the interactive simulation framework.

CONCLUSION

Herein, we developed an interactive tool for simulating a Spin-based ADC design, which is based on our previous research findings. We plan on utilizing our simulation framework in undergraduate and graduate coursework as well as to engage and attract high school students into STEM-related fields. The poster itself with full graphical information is available as a stand-alone pdf file. Please refer to the poster pdf file for full website information and screenshot figures. The website URL for these materials and the simulation framework itself is located at: http://cal.ucf.edu/ccsser.html. The work highlighted in the poster pdf file reflects the system at the time of publication, while the website continues to be updated with additional features.

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