MRAM-based Stochastic Oscillators for Adaptive Non-Uniform Sampling of Sparse Signals in IoT Applications

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Motivation
Need for CS solutions considering device-level constraints for IoT

- Maximize signal sensing and reconstruction performance while reducing energy consumption for Internet of Things (IoT) applications

- Solutions like Compressive Sensing (CS) reduces number of samples per frame to decrease energy, storage, and data transmission overheads

- Non-uniform CS in hardware requires Random Number Generator (RNG)
  - True RNGs (TRNGs)
  - Pseudo RNGs (PRNGs)

Adaptive Sampling of Sparse IoT signals via STochastic-oscillators (ASSIST)
Sparse signals are common in applications such as sensors and wireless spectrum sensing.

In real-world applications, signals may contain a Region of Interest (RoI) and uniform sampling is not efficient.

CS can be applied to RoI of signals, image, video, etc., identified by methods in literature.

Signal’s sparsity may be non-uniform.

Cornerstone to achieving high-accuracy and efficient CS is utilization of adaptive measurement matrix that changes according to signal characteristics extracted from previous time frames.

**ASSIST Approach**

**MRAM-based Stochastic Bitstream Generator as TRNG**

**✓ MRAM-based Stochastic Oscillator (MSO)**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation magnetization (CoFeB) ($M_s$)</td>
<td>1100 emu/cc</td>
</tr>
<tr>
<td>Free Layer diameter, thickness</td>
<td>22 nm, 2 nm</td>
</tr>
<tr>
<td>Polarization</td>
<td>0.59</td>
</tr>
<tr>
<td>TMR</td>
<td>110%</td>
</tr>
<tr>
<td>MTJ RA-product</td>
<td>$9 \Omega - \mu m^2$</td>
</tr>
<tr>
<td>Damping coefficient</td>
<td>0.01</td>
</tr>
<tr>
<td>Temperature</td>
<td>26.85°C</td>
</tr>
</tbody>
</table>

- Due to low energy-barrier, MTJ’s resistance level fluctuates between AP and P states
- Probability of output being ‘1’ can be controlled using $V_{IN}$

**✓ MRAM-based Stochastic Bitstream Generator**

- Power-Gated Clock (PG-CLK) controls number of MSO outputs
- $V_N$ can be used to adaptively adjust number of ‘1’s in $V_M$
ASSIST Approach
MRAM-based NVM for Storing CS Measurement Matrix

- Non-volatile complementary SHE-MRAM array offers wide read margin, increased reliability, and clockless read
- MRAM-based stochastic bitstream generator for columns
- Adjust $V_M$ to modify number of rows to account for signal’s sparsity rate
- Adjust $V_N$ to increase accuracy of RoI sensing and reconstruction
Simulation Results
MRAM-based Stochastic Oscillator and MRAM-based NVM

- NVM bit-cell requires **155.2fJ** write energy and **21.9fJ** read energy, on average
- NVM bit-cell **standby energy** is **36.4aJ**
- MSO reduces energy consumption per bit by 9-fold and reduces area by 3-fold, on average, compared to state-of-the-art TRNGs

<table>
<thead>
<tr>
<th>Design</th>
<th>Technology ($V_{DD}$)</th>
<th>Energy$_{norm}$</th>
<th>Area$_{norm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>28nm (1.0V)</td>
<td>0.3X</td>
<td>1.25X</td>
</tr>
<tr>
<td>[2]</td>
<td>28nm (1.0V)</td>
<td>8.9X</td>
<td>4.8X</td>
</tr>
<tr>
<td>[3]</td>
<td>28nm (1.0V)</td>
<td>17.4X</td>
<td>3.7X</td>
</tr>
<tr>
<td>This Work</td>
<td>14nm (0.8V)</td>
<td><strong>1X</strong></td>
<td><strong>1X</strong></td>
</tr>
</tbody>
</table>

Simulation Results
ASSIST Approach via CS with RoI

- ASSIST decreases Time-Averaged Normalized Mean Squared Error (TNMSE) of RoI coefficients up to 2dB\(^*\) at cost of reduced performance on total recovery error
  - N = 200 and various undersampling ratios, M/N
  - Sparsity level of k/N = 0.1 and RoI occupying 10% of entire signal
- For smaller undersampling ratios, ASSIST incurs no performance degradation compared to uniform CS for non-RoI entries

Simulation Results
Process Variation Reliability Analysis of MRAM-based NVM

1,000 Monte Carlo simulations considering:

- 10% variation on threshold voltage of CMOS transistors
- 1% variation on width and length of CMOS transistors
- 10% variation for MTJ’s dimensions

Results:

1) since states of MTJs are Complementary, they provide large sense margin, resulting in <0.001% read errors
2) Complementary SHE-MRAM provides reliable write performance resulting in <0.001% write errors
3) Complementary SHE-MRAM does not suffer from read disturbance error due to small read current compared to write current
Conclusion

ASSIST for Low-Power and Area-Efficient IoT Applications

- **ASSIST** offers a spin-based non-uniform CS circuit-algorithm solution that considers signal dependent and hardware constraints.

- **MRAM-based Stochastic Oscillator** as a TRNG provides 3-fold area improvement while achieving 9-fold reduction in energy consumption per bit compared to similar TRNGs in the literature.

- In **ASSIST**, sensing energy is distributed less wastefully by assigning more sensing energy to coefficients in RoI.

- Our circuit-algorithm simulation results indicate non-uniform recovery of original signals with varying sparsity rates and noise levels.

![Diagram of ASSIST circuit](image)
BACKUP
Importance level of the coefficients and RoI are inferred using a Bayesian data mining framework**

Design measurement matrix such that more important coefficients with more sensing energy can be recovered

Exploit temporal and spatial correlation to design measurement matrix at each step to sample more intelligently

Bayesian Inference: Given the effect/output find the cause/input

Using Bayesian inference, we predict the RoI from history of signal at each frame