Circuit architectures for *Beyond CMOS electronic devices*: Learning from biological systems toward creating robust electronic systems with fault-prone building blocks

Abstract:

Nano-electronic devices are viewed as promising building blocks for the next generation of so-called *Beyond CMOS LSIs*. The *Beyond CMOS devices* include single-electron devices, which operate by regulating the flow of single or a few electrons. Single-electron circuits are thus viewed as promising building units for ultra-low power electronic systems. In addition, because of the high device integration, resulting from the minute physical sizes of individual devices, single-electron devices have the potential for applications in parallel-signal processing systems that not only require a high density of replicated devices, but also low power consumption per unit area. In spite of these inherent advantages, however, single-electron devices suffer from high fabrication mismatches (i.e. variance in physical parameters of fabricated devices), and also have low tolerance to internal and external noises. Therefore to effectively utilize the merits of single-electron devices in creating reliable and efficient electronic systems, there is need to come up with a method to either (i) eradicate these set backs through improved fabrication techniques or (ii) compensate for the drawbacks through additional circuitry incorporated into the systems. The former approach might not provide a long lasting solution due to the complexity of present technologies. On the other hand, the latter approach would result in complicated system architectures, consequently increasing power consumption of the entire system. A novel approach would be to effectively utilize heterogeneity as a result of process mismatches, internal noises emanating from thermal or other environmental noises to create new circuit architectures.

If we look at how neuronal systems function, there is an enormous amount of heterogeneity in the intrinsic response properties of individual neurons; they have diverse variances in firing rates, some of the neurons are even defective and they continuously receive noises from neighboring neurons through coupling synapses. However, in spite of these set backs, neural systems accurately encode signals as they are relayed from sensory organs to the central nervous system, or to other organs. A number of reports suggest that neurons in fact employ heterogeneity and synaptic noises to increase the fidelity of signal encoding. For example, Hospedales et al. ([1]) demonstrated that neurons in the vestibulo-ocular reflex (VOR) can encode high frequency signals with a high temporal precision as a result of their heterogeneity, while Mar et. al., ([2]) demonstrated that neurons employ heterogeneity to increase the signal-to-noise ratio in carrying out 1-bit analog to digital conversion (pulse-density modulation).

In our study toward establishing new circuit architectures for single-electron devices, we have investigated the implications of device physical parameter heterogeneity and thermal noises in improving the signal-to-noise ratio in a single-electron pulse-density modulation circuit ([3]). Furthermore, we investigate the implications of parameter heterogeneity in reliable transmission of signals in an ensemble of single-electron neurons.

Through Monte-Carlo based computer simulations, we have confirmed that heterogeneity in device physical parameters and the presence of thermal noises indeed reduce synchrony among individual neurons, consequently (i) increasing the temporal fidelity with which neurons can encode input signals with frequencies higher than the intrinsic response frequencies of individual neurons and (ii) improving the signal-to-noise ratio in pulse-density modulation.

References:

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3. A.K. Kikombo et al., "A neuromorphic single-electron circuit for noise-shaping pulse-density modulation", Int. J. of Nanotechnology and Molecular Computation, vol. 1 80-92 (2009).