Distributed Integrated Circuit Design for the 21st Century

by Ali Hajimiri

Ten years ago, we noticed that a significant milestone was on the horizon. It arrived a few years ago when the cut-off wavelengths of silicon transistors became smaller than the dimensions of typical chips implemented in those processes[1]. This crossover had fundamental implications in terms of the way high-frequency silicon-based circuits should and will be architectured and designed in the coming decade, making it possible to address a broad range of applications. Moreover, on account of the remarkable progress in the field of integrated circuits, it is possible to integrate more than a billion functional transistors capable of operating at mm-wave frequencies on a single silicon die. This (practically) unlimited number of high-speed transistors combined with the crossing-over of chip-size and cut-off-wavelength has produced unique opportunity that is just beginning to be harnessed.

Many new and existing applications can benefit from high-frequency, distributed circuits implemented in silicon. There are sensing and ranging applications using mm-wave frequencies. For instance, low-cost, highly integrated radars in applications such as automotive radar have received a great deal of interest in the recent years[2, 3, 4]. Automotive radars can be used in a broad range of applications, e.g., early warning and brake priming, self-parking, global traffic control, low-visibility driving aid, autonomous cruise control, and collision avoidance. On the communication side, in addition to traditional multi-gigabit data transmission, new direction-dependent modulation schemes, such as near-field direct-antenna modulation[5], can make it possible to create secure and power efficient data streams with concurrent full-rate transmission in several directions. Integrated power generation at high frequencies is another major challenge that has been helped by distributed integrated circuits. Finally, mm-wave silicon-based circuits can find applications in security, medical imaging and bio-chemical sensors.

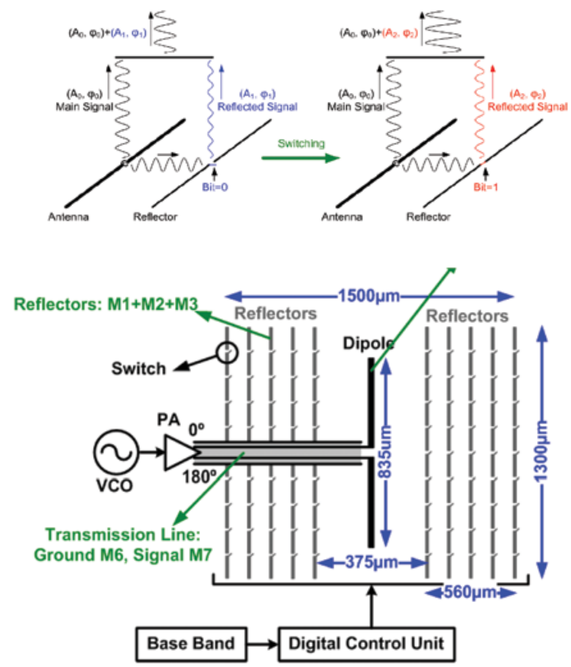

Figure 1: (a) simple one bit direct antenna modulation with a single switch. (b) 90-bit modulation at 60GHz

To take full advantage of the opportunities offered by the die-size wavelength crossover, one must retool for a new era. The artificial borders between electromagnetics, antenna, propagation, device physics, as well as analog and digital circuit design must be removed. These levels of abstraction, originally established to partition the overall system design into tractable tasks, are no longer valid at mm-frequencies and above. This new global design approach provides a larger design space and enables architectures and topologies with better performance and new features. The Lee center supported work to developed not only this new design approach, but also its application to several new CMOS-based technologies. One of these is now described. Another is detailed later in a description of our startup company Axiom.

Near-field Digital Antenna Modulation

Conventional radio transmitters take information at a so-called baseband frequency and then up-convert and amplify that information to a stronger signal at the desired (higher) transmission frequency. This process requires upconversion mixers and perhaps more importantly a linear (or linearized) power amplifier. As the final step, the amplified signal is fed to an antenna that radiates the modulated signal in all directions, albeit with different gain factors and time delays.

The near-field digital antenna modulation technique is a fundamentally different approach to data transmission that applies the signal directly at the antenna through digital manipulation of the electromagnetic boundary conditions[5]. By combining steps at the antenna it is possible to simplify the remainder of the transmitter since up-conversion mixers and linear power amplifiers are no longer required. The antenna modulation technique can also be used to create a secure communication channel by sending the desired data only in the intended direction, while a scrambled data stream is transmitted in other directions. Moreover, it can be used to concurrently transmit two (or multiple) streams of completely independent data in different directions both at the maximum rate, thereby increasing the overall transmitted data rate significantly. Finally, the simple design enables data transmission at high rates that are not limited by the bandwidth of the up-conversion chain.

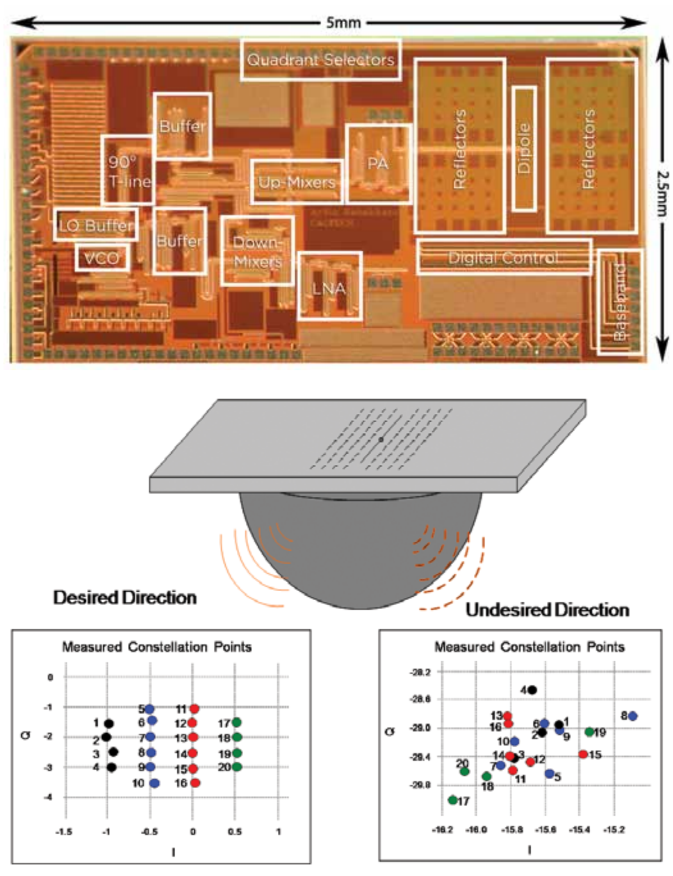

Figure 2: (a) die micrograph of a direct antenna modulation system at 60GHz implemented in silicon (b) measured signal constellations in the intended and unintended directions.

Figure 1 shows the basic principle behind the digital antenna modulation technique, where in this case a dipole antenna is driven by a continuous-wave signal of constant amplitude and phase. Also shown is a conductive metal line with comparable dimensions to the wavelength (i.e., a reflector) next to the antenna. This can be shorted or opened at some point along its length using a switch. The reflected signal interferes with the main signal radiated by the antenna in a given direction. The amplitude and phase of the reflected signal depend on the boundary conditions that the reflector imposes and can be varied in time by turning the digital switch on or off. These on/off states of the switch result in two different phases and amplitudes in the desired transmission direction. This provides a simple one-bit digital modulation without changing the output power or phase of the power amplifier driving the antenna. The amplifier therefore operates at its highest efficiency.

Although the single-reflector, single-switch configuration of Figure 1 provides basic binary modulation, it does so with only limited control over the direction and information content of the transmitted signal. A larger number of reflectors and switches in close proximity to the antenna makes it possible to precisely control the desired direction, and even transmit distinctly different information streams in different directions, simultaneously. This latter feature can be used to scramble the signal further in the unintended directions to implement a secure communication link by preventing an undesired eavesdropper from demodulating and recovering the signal.

The viability of this technique was demonstrated in an integrated circuit implementation[5] containing an on-chip dipole antenna with 10 reflectors. Each reflector featured 9 tuned MOS switches along its length, for a total of 90 switches and 2^{90} (~10^{27}) switching combinations. The chip and other details of the design are illustrated in Figure 2. The large number of switching combinations provides numerous ways to generate a desired point on what is called an information constellation (i.e., point in phase and amplitude) along a given direction. This, in turn, provides many additional degrees of freedom that can be used for concurrency or security. The ability to simultaneously send independent information to several directions at full rate using a single transmitter is not possible using conventional transmitter architectures.

This technology in which antenna reflectors are switched in the near field using a large number of very fast switches is a direct result of our ability to integrate, antennas, radio-frequency electronics, and digital circuits on the same substrate. This is but one example of the global co-design of electromagnetic structures with analog and digital circuitry. In practice, designing such system poses challenges not only at the architecture and circuit levels, but also with respect to the simulation tools and methodology. The Lee center seeded research on these ideas nearly 10 years ago, launching what has become a major new field within electronics. LEE

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Read more at: http://www.chic.caltech.edu

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