IC, Module, and Sytems Design for 100-300GHz MIMO Communications

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Rapidly increasing use of wireless communications is exhausting the presently allocated spectrum, hence the wireless industry is moving to 5G wireless systems, with carrier frequencies from below 6 toGHz to 86GHz. Research now considers next-generation systems with carrier frequencies between 100-300GHz. Capacity can be further increased over 5G, both because of the wide potentially available spectrum and because the short wavelengths permit compact arrays having many elements which can then support many simultaneous independent signal beams, this being known as massive spatial multiplexing or massive MIMO. Simple link budget analyses suggest that, with present state-of-the-art power- and low-noise amplifiers, aggregate capacities can approach or exceed 1Tb/s in short-range backhaul and endpoint links. The challenges in realizing such systems are in efficient digital beamforming, in the array physical design, and in realizing the front-end ICs and modules at low power consumption and low cost, particularly given the large number of required RF channels.

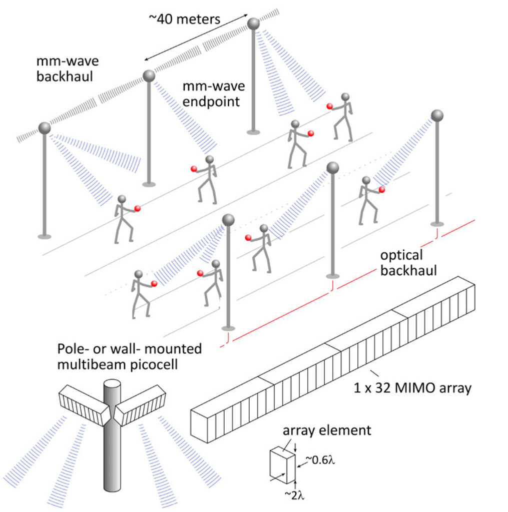


Figure 1: Spatially multiplexed network 140GHz picocell hub. The hub has 2 faces, each a 32-element MIMO array, each providing up to 16 independent signal beams. At 40m range, 10Gb/s transmission per beam is feasible with large operating margins.

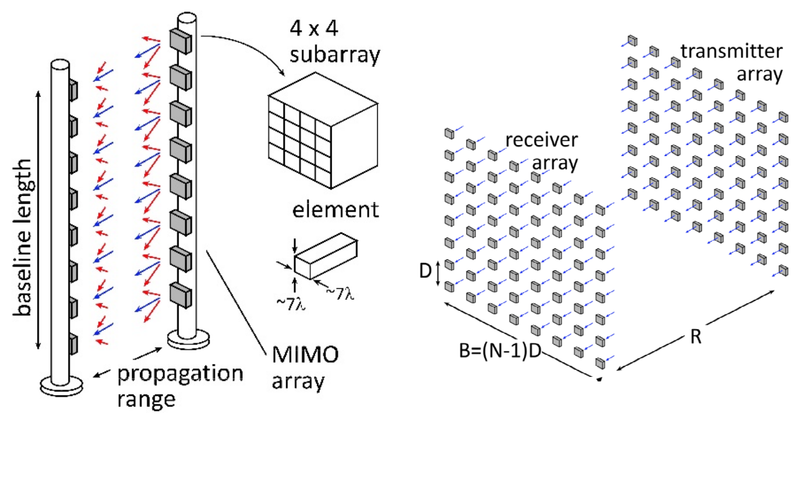


Figure 2: Spatially multiplexed wireless backhaul link, using (a) linear transmitter and receiver arrays, with each element being a 4×4 subarray. With a fixed range and baseline length, the maximum number of channels scales in proportion to the carrier frequency. Spatially multiplexed link using (b) a square array, with the number of channels scaling in proportion to the square of the carrier frequency.

Consider first [1] a 140GHz wireless communications hub serving many mobile users (Figure 1). Each array face has 32 elements and supports 16 users but is only 41mm long. If we assume that the hub's power amplifiers each provide 120mW at the 1dB gain compression point, that the handset has a 1cm^2 array (8×8 at $\lambda/2$ spacing) and has 8dB noise figure, that it is raining 50mm/hr., and that the signaling is QPSK at 10^{-3} uncoded error rate, then the hub can provide each user with 1Gb/s (10Gb/s) data rate at 110m (40m) range, even with 17dB total safety margins for partial beam blockage, equipment aging, and manufacturing variations. The net transmission capacity is 160Gb/s per array face. If we assume the same link parameters at 75GHz, keep the base station at 32 elements, but constrain the handset array to the same 1cm^2 area (4×4 elements at $\lambda/2$ spacing) as at 140GHz, then the same range is obtained at the same data rate; at 140GHz, it is more likely that the needed spectrum can be allocated.

Figure 2a shows a spatially multiplexed backhaul link. N transmitters, carrying independent data, form an array of length L. The receiver, at distance R, has a similar array but uses MIMO [2] beamforming. If the array angular resolution λ/L is smaller than the element apparent angular separation L/NR, then the signals can recovered without channel-channel crosstalk degrading the SNR. Link capacity is increased N:1. In a square array (Figure 2b), the capacity is increased N^2:1. Short wavelengths are of great advantage, as a short array can then carry many channels; at 500m range, an 8-element linear array must be 2.1m long at 210GHz, but 3.5m at 75GHz. At 210GHz, if each array element is an 8×8 subarray of 7λ by 7λ elements (for small beam angle adjustment) then, with 20 dB total margins, QPSK at 10^{-3} uncoded error rate, and 6dB receiver noise figure, transmitting 640Gb/s over 500m range in 50mm/hr. rain requires only 63 mW/element output power at the 1dB gain compression point. Given the same system parameters, the square array would transmit 5.1Tb/s but would require only 8 mW/element output power (P_{1dB}).

The MIMO systems considered above collectively carry many high-rate signal streams, hence signal-signal crosstalk from RF/IF/baseband signal chain nonlinearities (P_{1dB}, IP3), ADC/DAC resolution, and local oscillator phase noise are of potential concern. Yet, detailed systems simulations of the MIMO hub of Figure 1 indicate that, if received power leveling is employed, RF component 1dB gain compression points need only be 4dB above average power levels [3], that 3-4 bit ADC/DAC resolution is sufficient for QPSK transmission [3], and that the phase noise need be no smaller than that required of a single-channel system of the same symbol rate and constellation [4]. These findings suggest that the design requirements of the RF, IF, and baseband analog ICs are not particularly stringent. Given that ~16 high-rate (1-10Gb/s) user data streams must be recovered from ~32 wideband (I,Q) signals, the digital beam former might potentially be very computationally complex. Yet, with the development of computationally efficient beam space beamforming algorithms [5] and efficient VLSI digital implementations [6], high-rate all-digital MIMO beamforming appears to be feasible.

Even today's IC technologies can provide the frequency range, transmitter power and receiver noise required for the systems of figures 1-3; the challenge is in either realizing the ICs in lower-cost CMOS and SiGe technologies, or, if higher-performance InP or GaN [7] technologies are to be used, in bringing these to low cost and high production volumes. CMOS works well at 140-150GHz, [8] providing low receiver noise and moderate output power [9,10]; 140GHz arrays have been reported [9], but receiver noise and power amplifier output power and efficiency degrade at higher frequencies [11]. Best CMOS performance at 100-200GHz is for the 65nm through 22nm nodes. Longer-range ~150GHz wireless links can use CMOS with external InP HBT [12,13, 14, 15] or SiGe HBT power amplifiers [16,17] for increased output power; InP, in particular, provides record power and efficiency at these frequencies. InP HEMT or GaAs PHEMT or MHEMT low-noise amplifiers can be used for better receiver sensitivity [18]. For systems having >200GHz carrier frequencies, though CMOS can still be used for frequency conversion [19], for best performance, and to reduce the number of high-frequency IC-IC connections, it may be attractive to build the entire RF front end from III-V or SiGe technologies. Figure 3 shows some representative ICs, including full 200GHz transmitters and receivers [20] intended for MIMO backhaul links (Figure 2).

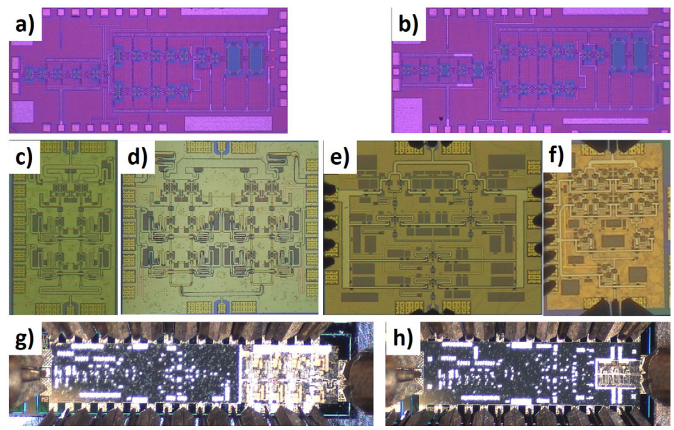
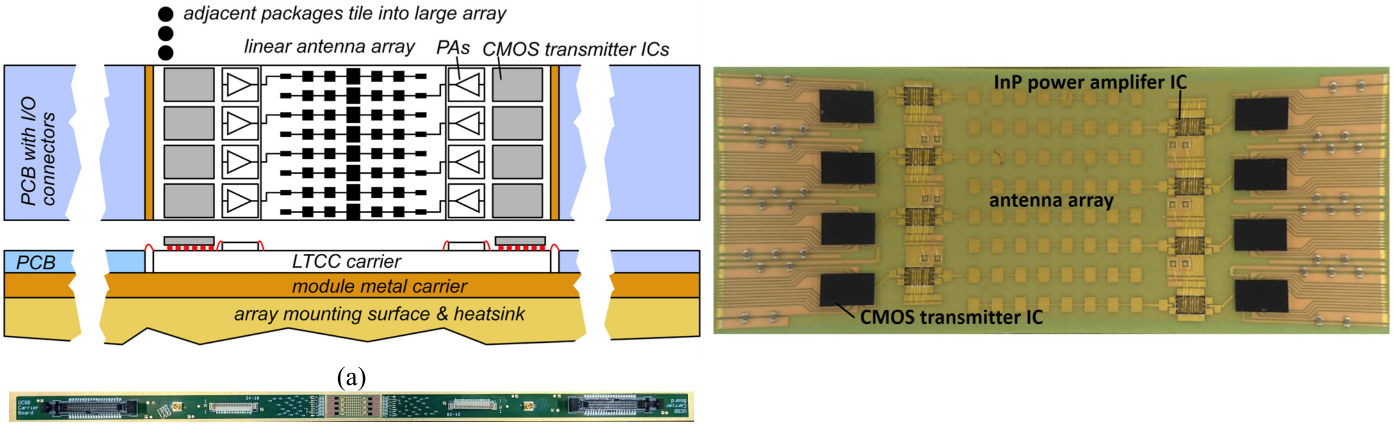


Figure 3: Representative 100-300GHz ICs, including a 140GHz receiver (a) and transmitter (b) in 22nm SOI CMOS, InP HBT power amplifiers at (c) 140GHz with 109mW power and 20.8% PAE, (d) 131GHz with 200mW power and 17.8% PAE, (e) 194GHz with 55mW power and 8.5% PAE, and (F) 266GHz with 48mW power and 4% PAE, and (g) a 200GHz transmitter with 34mW output power, and (h) a 200GHz receiver with 7.7-9.3dB noise figure, in 250nm InP HBT.

100-300GHz array transceivers present significant packaging challenges. To steer over 180^o both in azimuth and elevation, the array must be 2-dimensional and must have $\sim\lambda/2$ element spacing, ~1mm at 140GHz and 0.5mm at 300GHz. It is difficult to fit the necessary RF electronics in a small available area, and it can be difficult to remove the heat, particularly if inefficient or high-power PAs are used. If the users are mostly distributed over the ground, then the array is best designed to steer only in azimuth, and is then 1-dimensional (Figure 1). There is then sufficient space along the edges of the array both to fit the mm-wave font-end ICs and to remove the heat. Figure 4 shows an 8-channel transmitter array tile module designed 140GHz MIMO hubs (Figure 1). Experiments with these are in progress [21]. In MIMO backhaul links (Figure 2), phased-array beam steering in two planes over a small angular range can correct for small angular aiming errors from installation. For 10^o beam steering range, the elements can be spaced at $\sim 7\lambda$. Figure 5 shows an array tile design for this application, with linear arrays of antennas and ICs mounted on a metal tray, with trays then stacked to form a 2D array. We are presently developing versions of these modules both at 200GHz using previously-designed ICs [20] and at 280GHz using ICs now in development.



(a)

(b)

(c)

Figure 4: Eight-channel 140GHz MIMO hub transmitter array tile module: (a) schematic cross-section diagram showing the interface printed circuit boards, the LTCC carrier, connectors, and ICs, (b) photograph of the overall module, and (c) photograph of the LTCC carrier showing the antennas and CMOS and InP ICs. The overall module is 450mm × 15mm, while the LTCC carrier is approximately 12 mm × 33 mm

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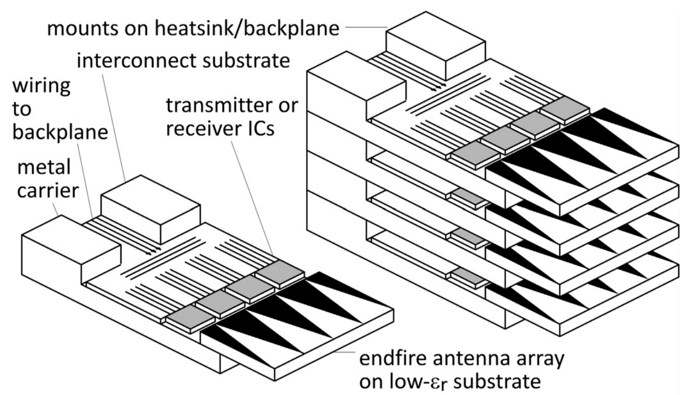

Figure 5: Array tile design with ~7λ spacing for small-angular-deviation 2D beam steering in fix-aimed point-point links.

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