Millimeter-Wave Massive MIMO: The Next Wireless Revolution?

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ABSTRACT

The combination of millimeter-wave communications, arrays with a massive number of antennas, and small cell geometries is a symbiotic convergence of technologies that has the potential to dramatically improve wireless access and throughput. This article outlines the benefits, challenges, and potential solutions associated with cellular networks that incorporate these technologies.

INTRODUCTION

To achieve the dramatic improvements in capacity and spectral efficiency needed for fifth generation (5G) systems to accommodate the ever increasing number of users who require ubiquitous access to high volumes of wireless data, three symbiotic technological directions are independently emerging [1]:

- Increasing frequency reuse through the creation of smaller cells, referred to as pico- and femtocells, with ranges on the order of 10–200 m
- Millimeter wave (mmWave) communications around and above 30 GHz where the spectrum is less crowded and greater bandwidths are available
- Base stations (BSs) equipped with a very large number of antennas (100 or more) that can simultaneously accommodate many co-channel users, an idea referred to as *massive* multiple-input multiple-output (MIMO)

Individually, each of these approaches could offer an order of magnitude increase in wireless capacity or more compared to current broadband systems; in combination with one another, one can envision achieving the approximate thousand-fold increase in capacity that will be needed in the coming decades. An encouraging factor is the apparent symbiosis between these three concepts: smaller cell sizes are attractive for the mmWave spectral band where RF path loss (PL) increases with frequency, the large beamforming gains achievable with very large antenna arrays can conversely extend coverage at longer ranges to help overcome the high mmWave path loss, the reduction in channel coherence time at mmWave frequencies is offset by the lower mobility and hence the higher channel coherence bandwidth due to operation in small cells, and the shorter wavelength associated with higher frequencies is appealing for massive MIMO transceiver designs since the physical dimensions of the antenna array and associated electronics are reduced in size.

There are, however, many questions and challenges that must be addressed before a system that leverages the above attributes could become a reality. These issues span the breadth of communications theory and engineering, from modulation, equalization, and interference management to antenna design and RF/analog/baseband processing. In this article, we explore the issues surrounding the idea of mmWave massive MIMO, and offer some potential solutions and research directions to consider.

THE MASSIVE MIMO IDEA

Increasing the capacity and reliability of wireless communications systems through the use of multiple antennas has been an active area of research for over 20 years. Multiple-input multiple-output wireless systems are now part of current standards and are deployed throughout the world. Typical MIMO installations use access points or BSs with relatively few (i.e., less than 10) antennas, and the corresponding improvement in spectral efficiency has been relatively modest. To achieve more dramatic gains, a grander view of the MIMO concept envisions the use of orders of magnitude more antennas (e.g., 100 or more) at each BS, a concept often referred to as *massive* MIMO [2]. The primary application envisioned for massive MIMO is in a cellular network, where a BS with a very large number N_t of antennas serves a set of single-antenna co-channel users. Asymptotic arguments are used to establish that, under certain conditions, as $N_t \to \infty$, "the effects of uncorrelated noise and fast fading vanish, throughput and the number of terminals are independent of the size of the cells, spectral efficiency is independent of bandwidth, and the required transmitted energy per bit vanishes" [3].

The advantages of massive MIMO can potentially be achieved using relatively simple signal processing approaches such as maximal ratio combining (MRC) and transmission (MRT). These conclusions typically assume ideal propagation environments with independent Rayleigh

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	PL for 35 GHz links in dB (required $N_tG_rG_t$ in dB)		PL for 60 GHz links in dB (required $N_tG_rG_t$ in dB)		PL for 140 GHz links in dB (required $N_tG_rG_t$ in dB)	
Distance (m)	PL (n = 2.5)	PL (n = 3)	PL (n = 2.5)	PL (n = 3)	PL (n = 2.5)	PL (n = 3)
R = 50	116 (31)	135 (50)	122 (37)	142 (57)	131 (46)	153 (68)
R = 100	124 (39)	144 (59)	130 (45)	151 (66)	139 (54)	162 (77)
R = 200	131 (46)	153 (68)	137 (52)	160 (75)	146 (61)	171 (86)
R = 500	141 (56)	165 (80)	147 (62)	172 (87)	156 (71)	183 (98)

Table 1. Path loss and required gains for n = 2.5 and n = 3 at various ranges for 35, 60, and 140 GHz.

Analog mmWave phased arrays have been designed and studied for various applications, but only very recently has work focused on digital beamforming and spatial multiplexing using MIMO techniques at mmWave frequencies, where adaptive control of the waveforms at each antenna is required.

fading, where wireless channels are inherently uncorrelated and even asymptotically orthogonal, but there is growing evidence that very high spectral efficiencies can still be achieved in real, non-ideal environments with a large but finite N_t. The issue of channel correlation would be especially critical in a mmWave implementation, where propagation tends to be line of sight (LOS) or near-LOS. While this would likely preclude the use of MRC and MRT for interference suppression, other methods based on zero-forcing (ZF) or minimum mean squared error (MMSE) beamforming can be employed to mitigate this factor and have been extensively studied.

A key advantage of the massive MIMO concept lies in its potential gains in energy efficiency. A user in a massive MIMO system with ideal channel state information (CSI) can theoretically achieve the same uplink throughput as with a single-antenna BS using only $1/N_t$ the required transmit power [4]. When an MMSE CSI estimate is used, the per-user power for the same throughput only scales as $1/\sqrt{N_t}$, which still represents a significant power savings at the consumer end. A similar scaling law also results for the downlink; in principle, for the same overall transmit power and desired receive signal-to-noise ratio (SNR), each individual power amplifier (PA) in the massive MIMO implementation needs to generate only $1/N_t$ of the total output power. This has significant implications in terms of design simplicity, cost, efficiency, and heat dissipation of the PAs. Alternatively, these gains in energy efficiency can be used to help overcome the larger path losses exhibited at mmWave frequencies and extend the system's operational range.

MIMO and Millimeter-Wave Communications

Most research in mmWave communications has focused on either LOS links with highly directional (e.g., dish) reflector antennas or short-range indoor applications. Analog mmWave phased arrays have been designed and studied for various applications, but only very recently has work focused on digital beamforming and spatial multiplexing using MIMO techniques at mmWave frequencies, where adaptive control of the waveforms at each antenna is required [5, 6].

A massive mmWave multi-antenna system would have a significantly smaller form factor than designs implemented at current frequencies, and would benefit from the orders of magnitude increases in available signal bandwidth. A major impediment to mmWave communications is PL and attenuation due to rain, foliage, and atmospheric absorption. Atmospheric attenuation due to oxygen absorption or heavy rain can be on the order of 10–20 dB/km. Fortunately, the emphasis on small cells with radii between 50–200 m means that these effects lead to only a few dB of additional loss in the very worst cases. For an mmWave massive MIMO system, it would primarily be free space PL that would ultimately impose an upper limit on cell size. Path loss can actually be beneficial in small-cell scenarios, since it limits intercell interference and allows greater frequency reuse. Conversely, as discussed below, deploying an array with a large number of antennas can provide array gain to extend the communication range and help overcome PL [7].

The ratio between received and total transmitted power evaluated at the antenna terminals of a communication downlink is given by

$$\frac{P_r}{P_t} = \frac{G_r G_t}{PL}, \tag{1}$$

where G_t and G_r are the transmit and receive antenna gains, respectively. Here, G_t represents the maximum gain of the entire transmit array, and thus is proportional to N_t. The path loss is given by $PL = 16\,\pi^2(R/\lambda)^n$ for a given range R, wavelength λ, and PL exponent n. In [8], which investigated mmWave propagation in urban environments at 28 and 38 GHz, PL exponents between 1.7 and 2.5 were noted in LOS cases, while N increased to 3.5–6 when the direct path was blocked. Table 1 shows the PL for several ranges at frequencies of 35, 60, and 140 GHz, assuming PL exponents of n = 2.5 and n = 3.

The large PL values must be compensated by 1) transmit power levels, 2) receiver sensitivity and low noise, and 3) high antenna/array gain. As an example, assume a maximum transmit power of 15 dBm for each RF chain and a receiver sensitivity of –70 dBm. For these values, the total gain in dB required to establish an RF link is shown in parentheses in Table 1 for each range and frequency. A system with N_t = 100 antennas provides an array gain of 20 dB, and one can assume a value of $G_r\,G_t$ = 30 dB for

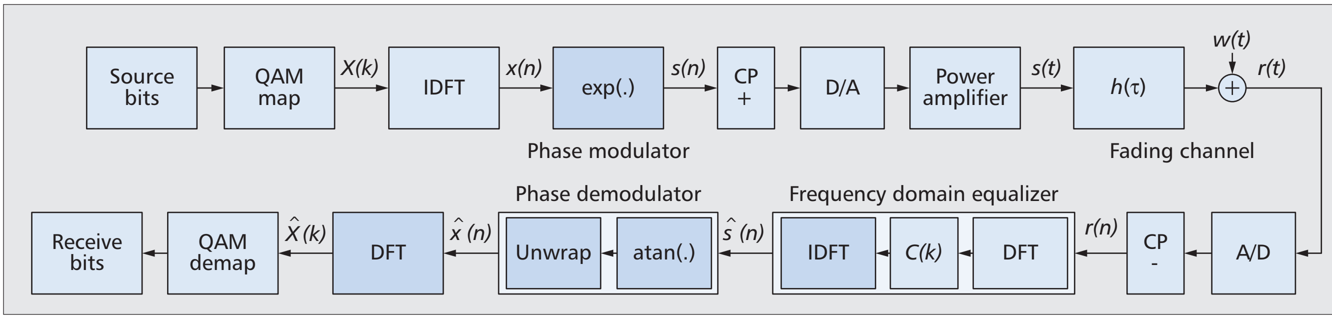

Figure 1. Baseband block diagram of a CE-OFDM system, based on a diagram from [10]. Darker blocks are added to a conventional OFDM implementation.

single-antenna users with simple RF hardware. Thus, we are looking for entries in Table 1 with required values for $N_t\ G_r\ G_t$ that are 50 dB or lower. With some margin to account for insertion loss and atmospheric attenuation, this translates into operational ranges of approximately 200, 100, and 75 m for 35, 60, and 140 GHz, respectively, for the worst case LOS channels ($n = 2.5$) observed in [8]. Such ranges are reasonable for typical pico- and femtocell geometries. (Note that the 200 m range derived for 35 GHz is consistent with measured values in [8].) In non-LOS environments where $n \geq 3$, reliable performance appears to be possible at the low end of the mmWave spectrum, although only for shorter ranges. While sufficient gain appears to be available for a wide range of mmWave frequencies in small cell applications, the number of users that can be serviced in this environment remains to be determined. In addition, the fact that mmWave signals do not penetrate brick and concrete means that mmWave cells may have to be located strictly indoors or strictly outdoors, a factor that could limit their application.

In the sections that follow, we examine various issues that would need to be considered in the design of a massive mmWave MIMO system, ranging from communication, signal processing, and system/circuit design factors.

Design Considerations for mmWave Massive MIMO Systems

Communication System

In the channel measurements taken at 28 and 38 GHz in [8], a wide range of delay spreads were observed depending on the measurement location. However, these measurements were taken without significant spatial selectivity; in a (near-) LOS environment, a massive MIMO array can provide a narrow beam that eliminates much of the multipath, in turn significantly reducing the delay spread and potentially reducing the need for equalization. However, since employing mmWave frequencies can allow dramatic increases in user bandwidth to hundreds of megahertz or even a few gigahertz (and hence symbol periods on the order of 1–10 ns or less), it is possible that even with a massive MIMO array, frequency selective fading may need to be addressed through either equalization or modulation.

Modulation and Energy Efficiency — As mentioned above, energy efficiency is one of the advantages driving much of the interest in massive MIMO. The high peak-to-average power ratio (PAPR) of orthogonal frequency-division multiplexing (OFDM) works against this advantage, and can impede good downlink performance. A recent study indicates that single-carrier modulation (SCM) can theoretically achieve near-optimal sum rate performance in massive MIMO systems operating at low-transmit-power-to-receiver-noise-power ratios, independent of the channel power delay profile and with an equalization-free receiver [9]. This is interesting for energy efficiency since SCM can be designed to have much better PAPR performance or even a constant envelope waveform. However, the results of [9] are based on the assumption of independent Rayleigh fading channels, which will not hold in the mmWave regime and could jeopardize the "equalization free" result. Furthermore, implementing SCM at mmWave frequencies implies very tight timing constraints on the order of a few nanoseconds or less, which is nontrivial. Thus, the trade-offs involved with using SCM for mmWave massive MIMO need further study.

Constant-Envelope OFDM — A switch to an SCM-based approach for 5G would be a significant departure from 4G systems, which are based on OFDM, exploiting its flexible resource allocation and simplified equalization. An alternative to SCM that eliminates PAPR and still allows one to maintain most of the advantages and functional blocks of OFDM is the so-called constant envelope OFDM (CE-OFDM) approach [10]. Figure 1 shows the block diagram of an uncoded CE-OFDM system; the lightly shaded blocks represent those used in conventional OFDM, while the darker shaded blocks are those that must be added for CE-OFDM. In this uncoded version, the source bits generate a complex-valued information sequence, $X[k]$, which is passed through an inverse discrete Fourier transform (IDFT) block and then phase modulated to generate the sequence $s[n]$. A cyclic prefix (CP) sequence is added as in standard OFDM, and the signal is transmitted. At the receiver, the CP is first removed, the DFT of the signal is generated, and equalization in the frequency domain is carried out. In order to undo the effect of the phase modulator, an oversampled IDFT, an arctan(·) operation, phase unwrapping, and a DFT (with subsequent subsampling) are performed. In essence, the OFDM waveform $X[k]$ is used to phase modulate rather than amplitude modulate the carrier.

It has been shown via simulations that CE-OFDM has better bit error rate (BER) performance than OFDM when used with realistic PA models and backoff values. It has also been shown that CE-OFDM has better fractional out-of-band power compared to OFDM. On the other hand, special care (e.g., oversampling, phase-locked loops) may be required in the phase demodulation and phase unwrapping process to avoid the FM threshold effect. While the PAPR benefits of CE-OFDM are especially promising for mmWave massive MIMO, more work is needed to determine its suitability for real deployments in terms of its bandwidth tradeoff, as well as the impact of phase noise and channel coding on performance. As discussed above, the ultimate choice of a modulation technique for mmWave massive MIMO is a complicated one, and whether a single-carrier system or a version of OFDM will become the preferred choice will depend on a large number of factors and further research.

SIGNAL PROCESSING

The degree to which an actual mmWave massive MIMO implementation can satisfy idealized theoretical assumptions will impact system performance. As discussed below, there are a number of signal processing issues that need to be addressed in this regard.

Channel Estimation — For very large N_t, channel estimation errors due to uncorrelated noise and interference are less problematic since the impact of such errors should vanish as $N_t \rightarrow \infty$. In massive MIMO systems, the primary source of CSI error is considered to be pilot contamination, where training sequences transmitted in adjacent cells are correlated with those from in-cell users. For mmWave frequencies, an interesting aspect is the degree to which high path loss and near-LOS propagation would mitigate the pilot contamination effect. Furthermore, a primarily LOS channel environment (via mmWave propagation or narrow antenna array beamwidths) could allow for channel estimation based on direction-of-arrival (DOA) estimation, which would do away with the need for pilot signals altogether, eliminating pilot contamination and training signals that consume bandwidth and reduce spectral efficiency. However, the advantages of a DOA-based approach would have to be weighed against the potential need to calibrate a large array and the added complexity of DOA estimation.

Channel Coherence Time and Bandwidth — Pico- and femtocell applications typically do not involve high-velocity users, but employing mmWave frequencies means that a given velocity will lead to a Doppler shift that is proportionately higher. Assuming an order of magnitude lower peak user velocity in a small cell and an order of magnitude increase in the carrier frequency, one could expect to see peak Doppler shifts similar to current macrocell applications (e.g., around 200 Hz). Thus, for pilot-based channel estimation, a rough estimate is that CSI would have to be updated at least as often as currently deployed MIMO systems. Of course, in a massive MIMO implementation there is more CSI to update, so the required computational rate would then increase as well. On the other hand, assuming narrow beams and LOS propagation, the channel coefficients are not subject to significant fading and would not vary as rapidly as in situations with appreciable multipath. The relatively slow variations in the direction of a given user's signal is another motivation for considering DOA-based channel estimation. Likely much more important than Doppler effects are time variations due to carrier frequency offsets and phase noise in the local oscillator (LO) distribution network governing the RF up- and down-conversion. A 200 Hz error at mmWave frequencies corresponds to an LO stability below 10 parts per billion, which is a stringent requirement. This will be a limiting factor unless sensitive phase and frequency tracking is employed.

Loss of Channel Orthogonality — Massive MIMO is based on the premise that as $N_t \rightarrow \infty$, under favorable propagation conditions, the individual user channels become spatially decorrelated and pairwise orthogonal. Theoretical studies of massive MIMO typically assume independent Rayleigh fading, which is hard to justify at mmWave frequencies. This suggests that user scheduling could be a critical component of mmWave massive MIMO systems in order to eliminate co-channel users with highly correlated channels. In one measurement study taken around 2–3 GHz, it was found that there is significant performance reduction when closely spaced users are present with an LOS path to the BS; instead of achieving 80–90 percent of the capacity, performance dropped to about 55 percent. Nevertheless, the study concluded that despite significant differences between the ideal and measured channels, a large fraction of the theoretical performance gains of large antenna arrays is still achievable.

Interference Management — There are several factors that may mitigate interference management in a mmWave massive MIMO implementation:
- Due to increased PL, signals at mmWave frequencies have limited range and thus allow for higher frequency reuse.
- Shadowing effects due to LOS or near-LOS propagation will reduce leakage into adjacent cells.
- The sheer volume of spectrum available at mmWave frequencies should lead to relaxed frequency reuse constraints.
- Beamforming with a massive MIMO array leads to narrow beamwidths and high spatial selectivity, which limits exposure of the signals to unintended receivers.

Nonetheless, it is not difficult to envision scenarios where small adjacent mmWave massive MIMO cells have significant LOS overlap, and where a unity frequency reuse factor is employed to maximize capacity. As such, there will be a

The ultimate choice of a modulation technique for mmWave massive MIMO is a complicated one, and whether a single-carrier system or a version of OFDM will become the preferred choice will depend on a large number of factors and further research.

No prior work has yet been reported on the design and fabrication of a complete massive MMW MIMO transceiver, covering aspects such as antenna layout, array geometries, RF front-end architectures, local oscillator distribution, optimization of power dissipation, demodulation, baseband processing, sampling and multichannel data aggregation.

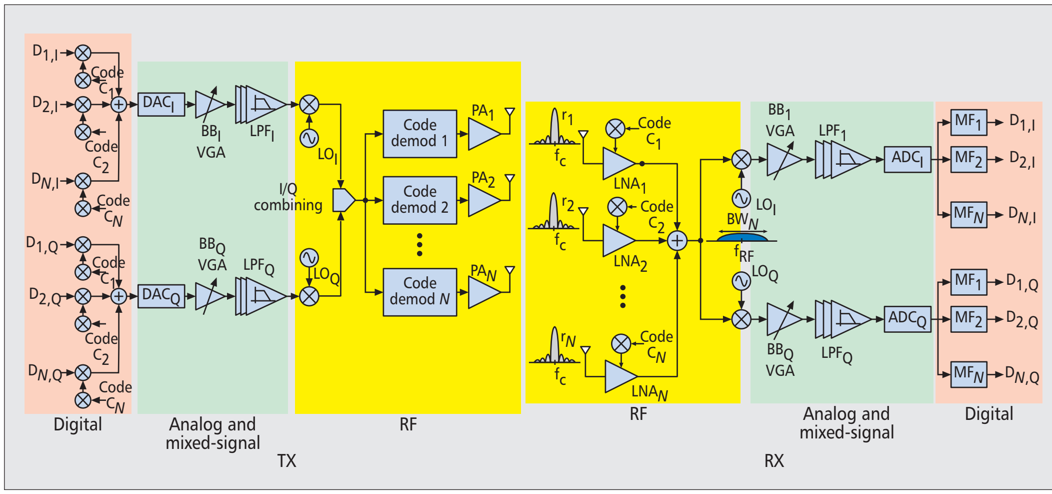

Figure 2. Block diagram of the TX and RX code modulated path sharing RF subsystems.

need for interference mitigation in these networks. Potential approaches could exploit the large number of degrees of freedom available in a massive MIMO array to use subspace-based and interference alignment methods.

Backhaul Transmissions — MmWave massive MIMO can be beneficial in providing very high-throughput backhaul in areas where it is too costly to install wire or fiber connections [11]. Massive MIMO arrays could be arranged to relay information back and forth between cells or to nearby network hubs. Such an approach would have considerable advantages over microwave backhaul links that employ dish antennas and physical antenna alignment; cooperating massive MIMO arrays could adaptively modify their transmit and receive beams to account for changes in the environment without a physical readjustment of the array, and they could simultaneously communicate with multiple backhaul stations since their beams are electronically steerable.

Antenna and RF Transceiver Architecture

The assumptions underlying the theory of mmWave massive MIMO communications will drive many aspects of the transceiver design, such as the need for high-efficiency antennas, low mutual coupling and RF channel crosstalk, stable and coherent LO distribution, sharing of transceiver resources, modular and easily scalable architectures, tight RF and antenna integration, as well as the choice of carrier frequency, signal bandwidth, antenna directivity, antenna geometry, array size, and so on. Some initial work has investigated the impact of phase noise, mutual coupling, and unstructured statistical hardware errors, but such studies have been limited to models rather than actual transceiver implementations. No prior work has yet been reported on the design and fabrication of a complete massive mmWave MIMO transceiver, covering aspects such as antenna layout, array geometries, RF front-end architectures, local oscillator distribution, optimization of power dissipation, demodulation, baseband processing, sampling, and multichannel data aggregation.

In the discussion below, we briefly describe some of the issues related to transceiver and antenna design in mmWave massive MIMO, and offer some ideas of potential directions to pursue.

An RF Path Sharing Transceiver Architecture — A major impediment to using conventional multi-antenna transceivers in a massive MIMO implementation is the need to replicate multiple transmit/receive (TRX) chains, one for each antenna. Conventional designs would need proportionately higher power consumption, chip area, input/output and control signaling, LO routing and distribution, and so on. This strongly suggests that implementation of massive MIMO transceivers will encounter a roadblock unless innovative solutions are explored to share RF resources.

A possible approach to addressing the above problem is the code modulated path sharing multi-antenna (CPMA) architecture of [12, 13], in which code multiplexing is used to combine the signals for multiple antenna subsets into a single RF/intermediate frequency (IF)/baseband/analog-to digital converter (ADC) path. The primary advantages of CPMA include a significant reduction in area and power consumption, and the path sharing of multiple RF signals mitigates issues associated with LO routing/distribution and crosstalk between RF chains. Figure 2 shows an exemplary block diagram of the CPMA TRX for a massive MIMO BS. The CPMA architecture subdivides the antenna array into groups of N antennas, and uses code multiplexing to combine the N signals onto a single RF path. Prior to transmission, the signal for a given antenna is extracted using an RF code demodulator. The code demodulators are designed using sub-nanosecond delay cells with flat group delay across the signal bandwidth. The process is reversed for the RX: each antenna output is first multiplied by a unique code sequence whose chip rate is N times the symbol rate, combined and then sent through the shared RF I/Q paths. The I/Q data is passed through separate ADCs, after which the digital baseband outputs of the individual antennas are recovered using code-matched filters.

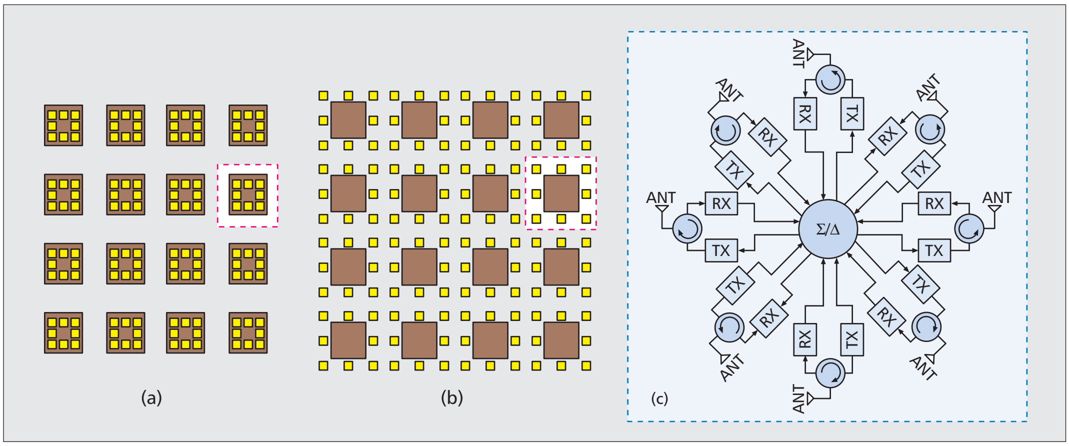

Figure 3. a) Possible distribution of 4 × 4 RF chips (brown squares), each with 8 antennas in the package (yellow squares); b) possible distribution of 4 × 4 RF chips, each with 8 antennas mounted nearby on a circuit board or on a different substrate; c) clock diagram for a *single chip*, including TX and RX chains, sharing antennas around the chip.

High directivity in a massive MIMO basestation is achieved by an aggregate use of all antennas via beamforming. This implies that each antenna cannot be large compared to the wavelength, but also not too small and isotropic since some gain is needed to overcome the large path loss.

The CPMA approach reduces the number of RF/IF paths and ADC/DACs by a factor of N, at the cost of increased bandwidth, higher-rate ADC/DACs, and the use of high-frequency RF code modulators and demodulators. While the increase in bandwidth does not necessarily impact chip area, it does increase power consumption. The power savings from reducing the number of RF chains is offset to some degree by the corresponding increase in bandwidth, but there is still a significant power advantage for the CPMA approach. For the TRX baseband, bandwidth is nearly proportional to power dissipation, and thus the dissipation of the CPMA subsystem is comparable to its conventional N-antenna counterpart. However, power consumption in the RF/IF subsystem is dominated by the maximum operational frequency $f_c + BW/2$, where f_c is the carrier frequency and BW represents the signal bandwidth. Since we are focused on mmWave applications where $N \times BW \ll f_c$, power will only be affected weakly by the bandwidth expansion. Consequently, replacing N blocks at center frequency f_c and bandwidth BW with one block at center frequency f_c and bandwidth $N \times BW$ will reduce the overall power consumption by a factor of nearly N compared to the conventional receiver.

Antenna Front-End Integration — High directivity in a massive MIMO BS is achieved by aggregate use of all antennas via beamforming. This implies that each antenna cannot be large compared to the wavelength, but also not too small and isotropic since some gain is needed to overcome the large path loss. We foresee two general solutions for high integration of antennas and RF front-ends depending on the operational frequency. For medium to high mmWave frequencies, antennas need to be located very close to their on-chip RF active components. At lower frequencies, the antennas can be located off-chip, although still in close proximity. These two choices will have an impact on various design aspects such as efficiency and insertion loss.

Figures 3a and 3b show two example architectures for a massive MIMO array of 128 antennas. A 4 × 4 configuration of RF chips is shown, each chip implementing a CPMA cluster of $N = 8$ antennas as discussed above. The first solution in Fig. 3a would be implemented at very high frequencies, where the insertion loss to bring the signal off-chip to an antenna would be too high. Therefore, the antennas (yellow squares) are better integrated into the chip package (brown squares) via either interconnects or electromagnetic (EM) coupling using near-fields. The second solution shown in Fig. 3b is suitable for lower frequencies. The antennas are located next to the RF chip, on a printed circuit board or on a different substrate in a different physical plane of the RF chip. This solution is favorable at lower mmWave frequencies where antennas are larger and not completely integrable within the chip package. In the latter solution, antenna design is more flexible, but the length of the RF waveguide connecting the chip to the antenna should be minimized. At medium and high mmWave frequencies, one could also consider a larger number of antennas per cluster because of their smaller footprint. Figure 3c shows a block diagram of the RF front-end with both TX and RX channels integrated within the same chip, and connected to 8 antennas in either configuration a or b. Whatever configuration is considered, mutual coupling is a concern and has been shown to theoretically limit the gains that can be achieved with massive MIMO.

Alternative Architectures — Other approaches exist for addressing the hardware requirements associated with handling massively parallel RF channels. One such approach based on the use of a discrete lens array (DLA) was recently constructed and experimentally analyzed in [14]. A planar DLA is used to generate narrow beams whose outputs are combined into a small number of digital channels via beamspace processing. Other hybrid analog/digital beamforming architectures have also been proposed that trade off signal processing flexibility (e.g., constrained or simplified precoding) for hardware complexity [5, 6]. Another alternative is the use of parasitic

While significant challenges remain, there is strong evidence to suggest that the combination of small cell geometries, MMW frequencies, and massive MIMO arrays could potentially lead to orders of magnitude increases in capacity and spectral efficiency for broadband wireless communications.

antenna arrays [15], which actually exploit the presence of mutual coupling between active antenna elements and neighboring passive ones. Such an approach could allow a small number of active antennas to achieve a higher degree of spatial multiplexing or beamforming gain by carefully controlling the coupling with adjacent parasitic antenna elements.

Conclusions

While significant challenges remain, there is strong evidence to suggest that the combination of small cell geometries, mmWave frequencies, and massive MIMO arrays could potentially lead to orders of magnitude increases in capacity and spectral efficiency for broadband wireless communications. In addition to improving overall raw throughput, such systems would also have advantages in terms of compact dimensions, energy efficiency, flexibility, and adaptivity that would make them ideally suited for a variety of pico- and femtocell applications. Research is needed on many fronts in order to assess the potential opportunities of mmWave massive MIMO systems. For example, to maintain the energy efficiency gains, an mmWave massive MIMO implementation may be better suited for single- rather than multicarrier modulation or, as discussed above, constant-envelope variations of OFDM. The excess bandwidth available at mmWave frequencies provides opportunities for creativity and flexibility in signal design that is not possible in today's bandwidth-constrained scenarios. A host of signal processing issues related to channel estimation, interference mitigation, precoding, and multicell cooperation will need to be addressed differently due to the mmWave propagation environment and the use of higher data rates. Innovative and highly integrated antenna and circuit architectures will be required that are power-efficient, resilient to mutual coupling, and effectively handle the massive multiplication of data channels.

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