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ULTRA MASSIVE MIMO AS AN ALTERNATIVE TO ULTRA DENSE NETWORK: BENEFITS AND CHALLENGES

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Abstract. This publication contains a general overview of Ultra Massive MIMO (U-M-MIMO) communication technology development over the last decade and comparison of this technology with ultra-dense network communication. We proved that in free space, these two technologies are equivalent. However, taking into account real channel and other practical constrains, each technology has its own advantages and disadvantages. We provide our evaluation of spectral efficiency gain that Massive MIMO (M-MIMO) provides for different channel models (both sub 6GHz and mm Waves). We also outline major challenges faced by M-MIMO technologies, such as channel estimation, cost, and power consumption, and will present most up-to-date solution approaches to resolve these problems. We compare two approaches to reduce M-MIMO cost and power consumption: "hybrid beamforming" vs. "all digital solution" with low resolution ADC's and DAC's. We compare two possible modulations (Multi-Carrier vs. Single-Carrier) for M-MIMO.

Keywords: Ultra Massive MIMO, Ultra Dense Network, Antennas Phased Array, M-MIMO Channel Capacity, M-MIMO Channel Estimation, Hybrid Beamforming vs. All Digital solution for M-MIMO, Multi-Carrier vs. Single-Carrier Modulation for M-MIMO.

1. Introduction

Like the agrarian revolution and the industrial revolution, we live in an epoch of information revolution. According to Cisco Visual Networking Index (VNI) forecast, we expect 7 times growth of global mobile data traffic from 7 to 49 Exabyte's per month.

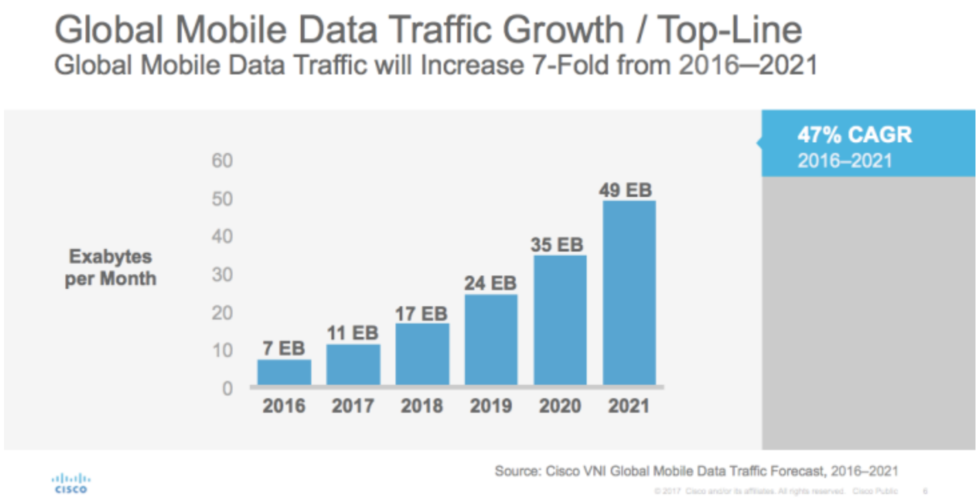

Fig. 1. Cisco VNI forecast for 2016-2021.

This exponential growth of mobile data traffic causes corresponding growth of radio spectrum cost that will force the industry to search for new methods to increase spectral efficiency and explore new frequency bands. According to information theory, the overall network capacity is restricted by Shannon limit:

$$C = K \cdot W \cdot \log_2(1 + SNR), \qquad (1)$$

where: SNR is the Signal to Noise Ratio,

W is the Channel Bandwidth,

K is the number of spatially orthogonal users .

Based on this equation, the development of new algorithms that increase receiver sensitivity (received SNR) will not provide significant increase of channel throughput because dependency of throughput from SNR is logarithmic. For example, in order to change modulation from 256-QAM 1024-QAM, we have to increase SNR at least by a factor of four (6db). However, the throughput growth is only 25 percent (from 8 bits per symbol to 10 bits per symbol). A much more beneficial approach is to explore new frequencies (increase channel bandwidth *W*) and generate more spatial diversity (increase parameter *K*). The increase of these two parameters will provide linear increase channel throughput.

There are two major technologies that enable new frequency bands exploration and increase spatial diversity:

- Ultra Dense network technology that increases overall network throughput by increasing the density of cells deployment [9]. Each cell respectively becomes smaller and, therefore, it may overcome path losses growth due to the exploration of new higher frequency bands. Additionally, the cells become smaller while the number of users that they may serve stays constant. Therefore, overall user's density grows.

- The Massive Multiple Input Multiple Output (M-MIMO) wireless communication refers to the idea of equipping cellular base station (BS) with a very large number of antennas - M. The large number of antennas provides an array gain which will be sufficient to overcome path loss growth due to the exploration of new higher frequency bands. It also makes more users spatially orthogonal and, therefore, increases overall user's density. The number of orthogonal users K that share common time and frequency resources is proportional to the number of antennas M.

These two technologies appear to be prime candidates for providing an order-of-magnitude increase of overall network throughput.

- Ultra dense network
- Ultra Massive MIMO

In the sequel, we demonstrate that in free space, these two technologies are equivalent in terms of energy efficiency given the same total number of antennas. We will also compare advantages and disadvantages of both technologies, taking into consideration practical fading channels and implementation constrains.

In the future, we should expect

- On the one hand, the cost of spectrum as a limited natural resource can only continue to increae.

- On other hand, the cost of antennas and associated RF and digital processing will continue to decrease as result of technological progres.

Therefore, M-MIMO, pioneered by T. Marzetta in 2010 [1] will certainly be one of the major technologies that provides solution to growing demand in mobile data traffic, and has become one of the major directions of modern wireless communication researches over the past 7 years.

2. M-MIMO Model

The MIMO channel is a multi-user one with a base station equipped with a large number of antennas, as shown in figure 2. It may be expressed as:

$$\begin{bmatrix} y_1 \\ y_2 \\ \cdots \\ y_M \end{bmatrix} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,K} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,K} \\ \cdots & \cdots & & \cdots \\ h_{M,1} & h_{M,2} & \cdots & h_{M,K} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ \cdots \\ x_K \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \cdots \\ n_M \end{bmatrix} \qquad (2)$$

or

$$Y = H \cdot X + N \quad , \qquad (3)$$

where:

X is the transmitted symbol vector with length K,

Y is the receiver antenna sample vector with length M,

N is the receiver noise sample vector with length M,

H is the channel matrix with size M by K,

K is the users number,

M is the base station antennas number. ($M >> K$).

In [1] it was shown that if the number of antennas M is sufficiently large and the number of users K is smaller than the number of antennas M, then channel autocorrelation matrix converges to be diagonal:

$$\lim_{M\to\infty}\left(H^H \cdot H\right) = I \qquad (4)$$

The channel of each user becomes orthogonal to that of the other users as the number of antenna elements grow, resulting in diminishing inter-user interference.

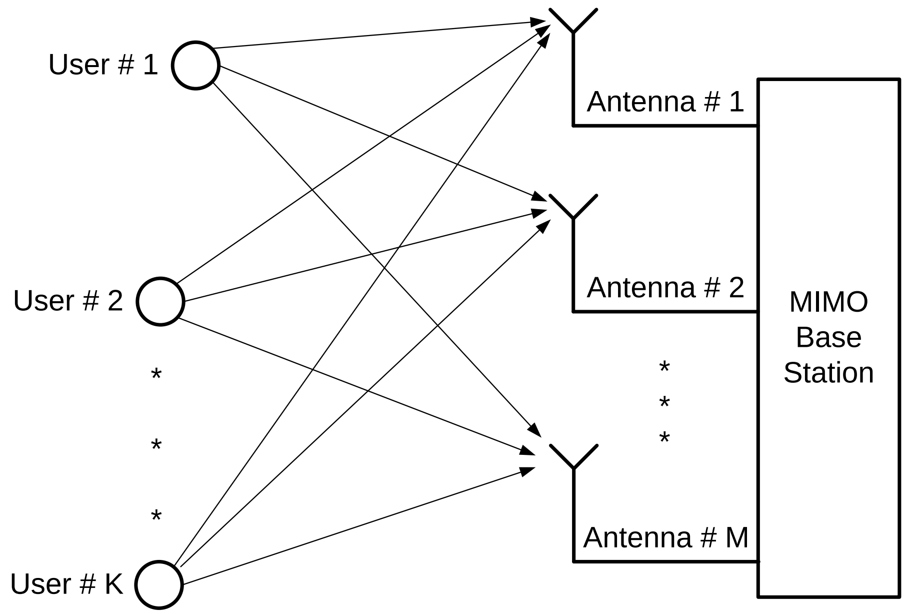

Fig. 2. Illustration of M-MIMO system.

Phased Antennas Array

A special case of M-MIMO when the physical size of the antennas array is much smaller than the array-user distance is properly termed a ‘phased antenna array’, as shown in Fig. 3. By applying appropriate steering coefficients to each antenna element, the array acts as a synthetic antenna with directional radiation pattern steered toward desired directions.

For a narrow band signal, the steering operation is given by:

$$y(\alpha,\beta)=\sum_{m=1}^{M} Str_m\left(f_0,\alpha,\beta\right)\cdot y_m \quad , \tag{5}$$

where the steering coefficient of antenna m is given by:

$$Str_m\left(f,\alpha,\beta\right)=\exp\left(j\cdot 2\cdot\pi\cdot f\cdot\tau_m(\alpha,\beta)\right) \tag{6}$$

$$\tau_m(\alpha,\beta)=\frac{x_m\cdot\cos(\alpha)\cdot\cos(\beta)+y_m\cdot\cos(\alpha)\cdot\sin(\beta)+z_m\cdot\sin(\alpha)}{c} \tag{7}$$

where:

(α,β) is the steering direction,

(x_m, y_m, z_m) is the spatial coordinate of antenna m,

f_0 is the carrier frequency,

c is the speed of light.

An ‘engine’ that accomplishes such steering is shown in Fig. 4.

Fig. 5 illustrates the radiation pattern of a square antenna array where spacing between antenna elements is equal to half the wavelength.

In this example, the size of the array takes on values of $8 \times 8 = 64$, $16 \times 16 = 256$ and $32 \times 32 = 1024$. The steering direction is 45 degrees in azimuth and 45 degrees in elevation. Since the array has the same size and the same steering direction in vertical and horizontal plane, it also has the same radiation pattern in vertical and horizontal plane.

From Fig. 5 we may see that the phase array form the beam steered to the desired direction (45 degrees in both orientations), and the width of this beam is inversely proportional to array size. The larger the size of the array, the narrower the beam width is, and thus the more the number of users who can share common frequency and time resources.

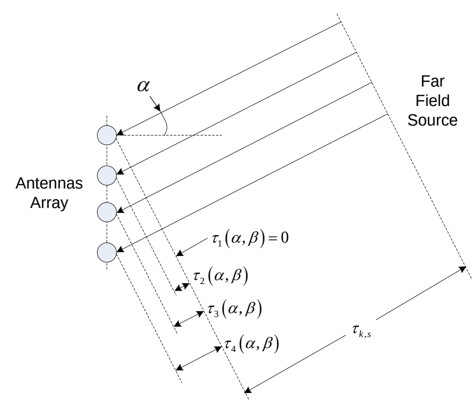

Fig. 3. Illustration of Phased Antennas Array.

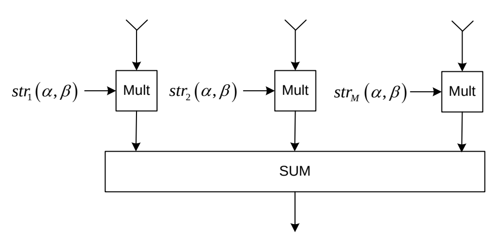

Fig. 4. Steering engine block diagram.

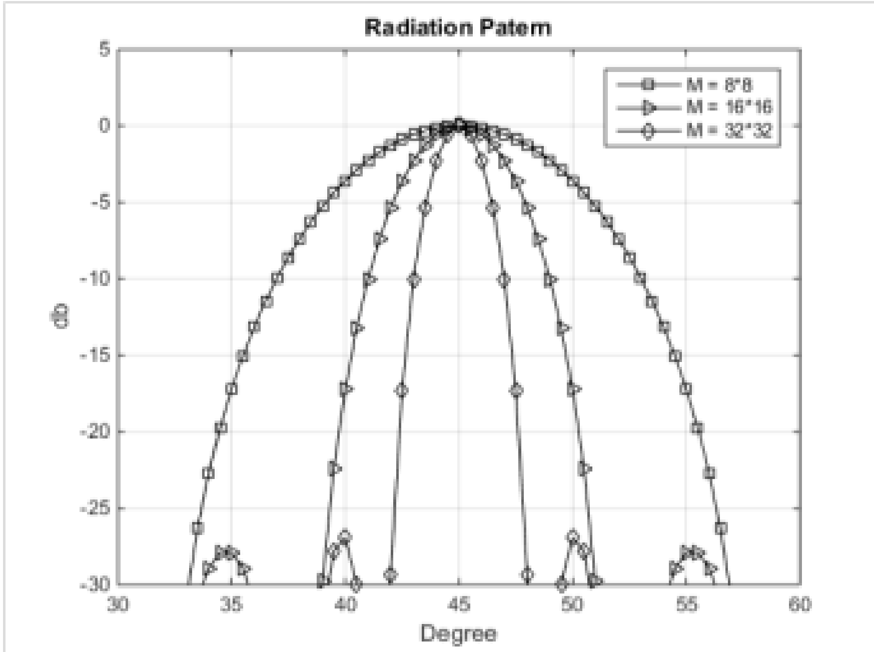

Fig. 5. Phase Array radiation pattern.

The phased array technology is well known since World War II. The theory and practice of phased array is given by, e.g. Van Tree [4]. It has a wide usage in radiolocation for military application. However, application for communication is new and emerges only in the context of M-MIMO.

Phased array technology is an important part of M-MIMO. However, it does not cover the practically relevant scenario where the physical size of an antennas array is comparable to the distance between the array and the users. For example, it does not cover distributed M-MIMO scenario where a user is surrounded by an array of distributed antennas, as illustrated in Fig. 6:

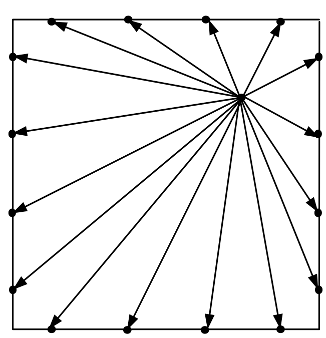

Fig. 6. The Distributed M-MIMO illustration.

3. M-MIMO benefits

A. *Spectral Efficency gain*

The actual M-MIMO performance gain depends on specific fading channel characteristics. Since M-MIMO idea was presented, numerous channel measurements have been collected [5, 6, 7]. Based on these results, standards bodies such as 3GPP specified spatial channel models, see, e.g. TR 36.873 [6]. In addition, plenty of measurement data for mm Wave bands are available. However, these measurements typically employ antenna array of fewer than 200 antenna elements, or by equivalent analog directional antennas. For larger M-MIMO arrays, additional measurements must be taken. Meanwhile, we attempt to extrapolate M-MIMO performance based on existing channel models on larger M-MIMO arrays.

We provide simulation with the following setup:

1. The carrier frequency is 2.1 GHz.
2. We assume that signal is sufficiently narrow band so that we may neglect inter symbol interference effect.
3. We use the following channel models:

- 3GPP 36.873 Rural [6],
- 3GPP 36.873 Urban Macro [6],
- 3GPP 36.873 Urban Micro [6],
- 76GHz mmWaves from [7].

The spatial channel model provides a list of beams with its amplitude, phase, delay, and angle of arrival. From these parameters we may calculate the channel of each antenna as superposition of all arriving beams.

4. We use circular antennas array with the following number of antennas: 4, 8, 16, 32, 64, 128, 256 and 1024, as shown in Fig. **7**.
5. The multi user receiver type is MMSE.
6. We assume perfect channel estimation.

7. We assume perfect power management so that each user has the same signal energy and SNR equal to 9db.

8. We increase the number of users who share common frequency and time resources until after MMSE signal to noise and interference ratio (SINR) reach a level of 3db lower than SNR: 6db.We count an average number of users whom we can serve without exceeding the SINR limit.

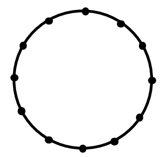

Fig. 7. Circular antennas array.

The simulation results are shown in figure 8,9,10 and 11, and lead to the following observations:

- The richer the channel multipath, the more users can be supported.
- The mm Wave channel result shows user saturation after 256 antennas, after which the increase of the number of antennas does not provide significant gain in the number of users.
- The results for the rest of the channels show little saturation, and the increase in the number of antennas provides significant gain in the number of users.

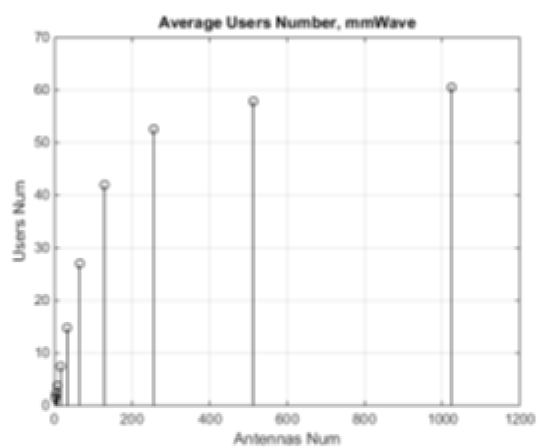

Fig. 8. Average number of users for mmWaves channel as function of the number of antennas.

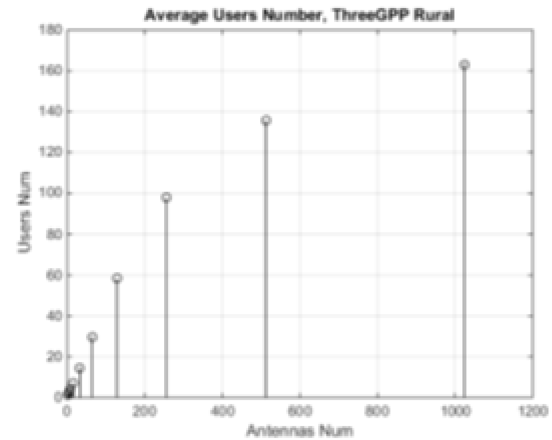

Fig. 9. Average number of user for 3GPP Rural channel as function of the number of antennas.

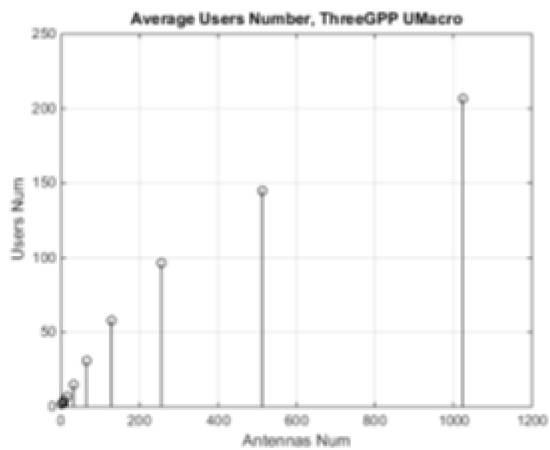

Fig. 10. Average number of user for 3GPP Urban Macro channel as function of the number of antennas.

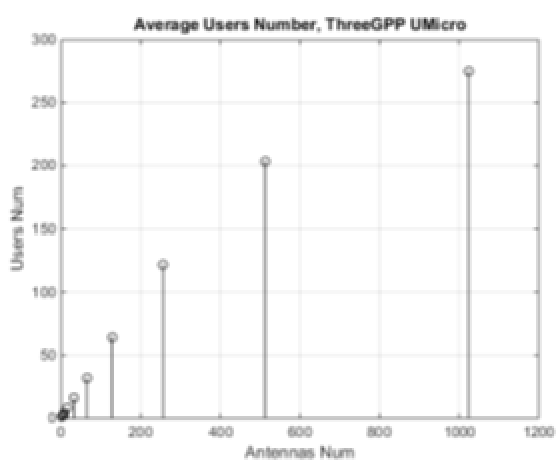

Fig. 11. Average number of user for 3GPP Urban Micro channel as function of the number of antennas.

B. *High Frequency Band Exploration*

The shortage of spectrum in the lower frequency bands has forced the industry to explore higher bands. However, the higher the frequency is, the higher the pass loss is. In order to compensate it we need larger antennas array. For array with fixed aperture, the pass loss increase is compensated by the increase of the number of antennas. In free space, both of them are proportional to square of carrier frequency. Thus, they compensate each other if the physical array apertures of the base station and the user terminal are both kept a constant, as shown below.

$$E_{RX}(\lambda) = E_{TX} + G_{ANT}(\lambda) - L_{CH}(\lambda), \tag{8}$$

where:

	E_{RX}	is the received signal,
	E_{TX}	is the transmitted signal energy,
	$G_{ANT}(\lambda)$	is the antenna array gain,
	$L_{CH}(\lambda)$	is the channel path losses,
	λ	is the carrier wavelength,
	R	is the channel distance,
	S	is the antenna array aperture,

$$G_{ANT}(\lambda) = 10 \cdot \log_{10}\left(\frac{2 \cdot \pi \cdot S}{\lambda^2}\right), \tag{9}$$

$$L_{CH}(\lambda) = 10 \cdot \log_{10}\left(\left(\frac{4 \cdot \pi \cdot R}{\lambda}\right)^2\right), \tag{10}$$

$$E_{RX}(\lambda) = E_{TX} + 10 \cdot \log_{10}\left(\frac{S}{2 \cdot \pi \cdot R^2}\right) = \text{const}. \tag{11}$$

However, the number of antennas per array with fixed aperture and spacing between antennas $(\lambda/2)$ is given by:

$$M = \frac{4 \cdot S}{\lambda^2} \tag{12}$$

It means that the higher the frequency, the more antennas we will have in an array with fixed aperture, implying that high frequency band exploration will lead to the increase of the size of M-MIMO array. Nowadays, mmWaves band (20GHz – 90GHz) arrays are becoming a reality. The mmWaves arrays employ hundreds of antennas. Meanwhile, development of new technologies, e.g. graphene, nano-antenna, has started. They promise operation with millions-antennas arrays into the THz range [8].

The figure below illustrates the deployment of 10,000 60GHz antennas array on a square of size 25cm by 25 cm.

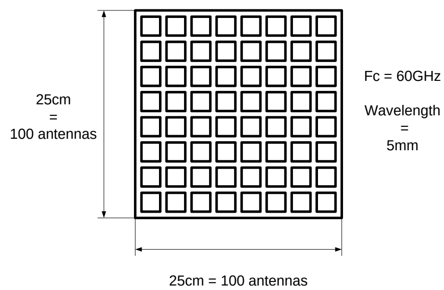

Fig. 12. 60 GHz antenna array deployment.

C. Ultra M-MIMO as an alternative to Ultra dense network

Let's consider M-MIMO free space link budget. In free space, according to (11) and (12), the maximal cell radius is given by:

$$R = \sqrt{M \cdot \lambda^2 \cdot E_{TX} / (0.5 \cdot \pi \cdot E_{RX})} \tag{13}$$

Therefore, the antennas density is given by:

$$D_A = M / (\pi \cdot R^2) = 0.5 \cdot E_{RX} / (\lambda^2 \cdot E_{TX}) \tag{14}$$

As we can see, the antennas density does not depend on the number of antennas. This means that in order to provide the same energy efficiency (constant transmitted power), we may use one big cell equipped with many antennas or many small cells each equipped with a small number of antennas. The antenna density will be the same.

In free space, with uniform distribution of users, the number of orthogonal channels that M-MIMO generates, K, is equal to the number of array antennas:

$$K = M \tag{15}$$

Therefore, the user's density D_U is equal to antennas density:

$$D_U = K/S = M/S = D_A \tag{16}$$

It means that in order to provide same user density, we may use one big cell equipped with many antennas or many small cells each equipped with a small number of antennas.

The idea to provide cellular coverage for growing number of users by using a large number of densely deployed base stations leads to the concept of ultra-dense cellular network. We may also reach the same goal with one base station equipped with many antennas (M-MIMO). As follows from (14) and (16), in free space these two solutions are equivalent. The figure below illustrates this equivalency.

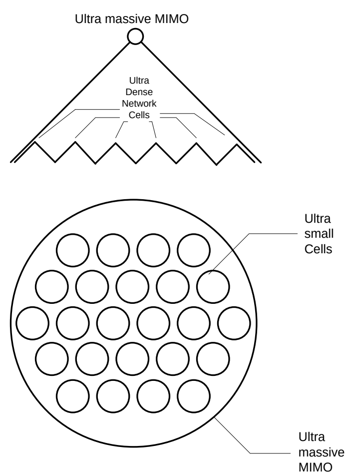

Fig. 13. Illustration of Ultra Massive MIMO and Ultra Dense Network equivalency.

We may use the perimeter of high buildings and city towers for the installation of ultra M-MIMO, as illustrated in the figure below

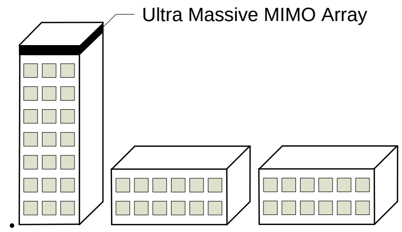

Fig. 14. Ultra Massive MIMO deployment.

Another option for ultra M-MIMO deployment is airborne platforms such as unmanned drones and airships [10]. There are recent activity in this field, as demonstrated by companies like Google [11] and Facebook [12]. The figure below illustrates airborne approach.

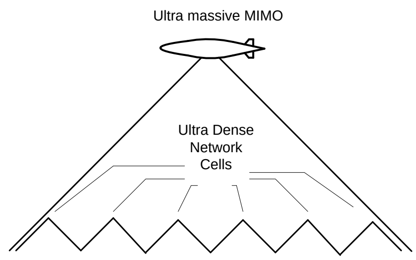

Fig. 15. Airborne Ultra Massive MIMO deployment.

It may turn out that in real network with real multipath channel, ultra dense network solution is more efficient than ultra M-MIMO. However, ultra M-MIMO has the following three advantages:

- It is much easier and cheaper to find a place for the installation of one big cell than many places for the deployment of a large number of small cells. According to [18] in Sweden in 2004, the price of installing a new cell-site is € 100.00, twice as much as the price of the equipment.
- It is much easier to provide backhaul connection to one large cell than to many small cells
- The ultra M-MIMO is much more convenient for the implementation of joint multi user decoding algorithms such as, for example, multi user interference suppression. For ultra-dense network, we require huge inter cell traffic to implement inter cell interference suppression.

These two technologies may be complimentary to each other by way of giving a provider an opportunity to make a decision as to which one of them better meets his need in each specific place.

4. M-MIMO challenges

A. Channel Estimation

In multi antenna communication, we get full signal energy only after coherent accumulation over all antennas. It means that signal to noise ratio (SNR) of each antenna is M times lower than the post-combining SNR. For example, if QPSK receiver is designed to operate with nominal SNR of 10db, and we are dealing with M-MIMO array of 1000 antennas, the SNR of each antenna is -20db. The classical method of uplink channel estimation cannot work at such a low SNR. Even an increase of pilot signal is not an option because we have to leave enough room for data transmission. Another problem that emerges in the context of M-MIMO is downlink channel estimation in FDD mode when we cannot use channel reciprocity to estimate downlink from uplink. According to classical downlink channel estimation methods, we need individual pilot to each transmitting antenna, which in M-MIMO case is impractical.

The solution to M-MIMO channel estimation problem is based on the fact that we estimate not just any arbitrary channel but a channel with certain spatial constrains. Beam domain channel estimation approach [13] applies multi beam channel model that represents a channel as superposition of a limited number of beams S with certain angle of arrival, delay, phase and amplitude.

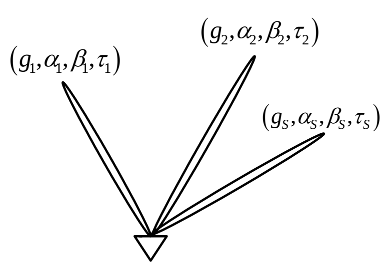

Fig. 16. Multi beam channel representation.

The multi beam up and down link channel is given by:

$$h_{UL,m}(t)=\sum_{s=1}^{S} g_{UL,s}\cdot Str_m\left(f_{UL},\alpha_s,\beta_s\right)\cdot\delta\left(t-\tau_s\right) \qquad (17)$$

$$h_{DL,m}(t)=\sum_{s=1}^{S} g_{DL,s}\cdot Str_m\left(f_{DL},\alpha_s,\beta_s\right)\cdot\delta\left(t-\tau_s\right) \tag{18}$$

where:

$h_{UL,m}(t)$ is the uplink channel of antenna *m*,

$h_{DL,m}(t)$ is the downlink channel of antenna *m*,

f_{UL} is the uplink carrier frequency,

f_{DL} is the downlink carrier frequency,

S is the number of beams,

$g_{UL,s}$ is the beam *s* uplink complex amplitude,

$g_{DL,s}$ is the beam *s* downlink complex amplitude,

(α_s,β_s) is the beam *s* angle of arrival,

τ_s is the beam *s* delay,

$Str_m(f,\alpha,\beta)$ is the steering function that is given by (6) and (7).

The uplink channel estimation includes two steps:

- Estimation channel spatial parameters $(g_s,\alpha_s,\beta_s,\tau_s)$ for all *S* beams.
- The reconstruction of down link channel from a list of spatial parameters according to expression (17).

For regular array with size *M* and the spacing of half wavelength between antennas, any channel may be represented as superposition of *M* orthogonal beams. The transformation from antenna to beam domain is linear transformation that does not cause any information losses. However, we put constrain that a channel consists only of *S* beams, and this number *S* is much smaller than *M*, the number of antennas. The additive noise is uniformly distributed in all directions. By choosing *S* strongest beams, we filter noise and reduce channel estimation error energy by a factor of *M/S*.

As we can see from expression (18), we may use channel reciprocity and take beams delay and angle of arrival estimation from uplink to downlink. For FDD downlink, we may estimate only S beams complex amplitudes that requires only S pilots, which is much less than the original M pilots for each antenna.

The multi beam MRC receiver may be represented as a spatial Rake receiver with one finger representing each beam, as shown in the figure below:

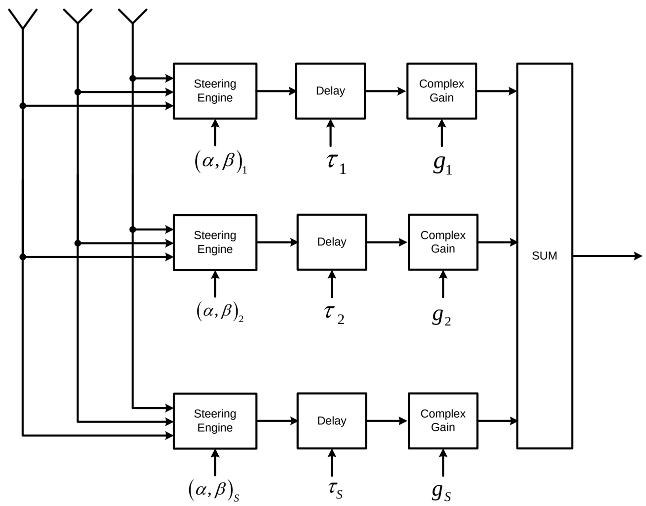

Fig. 17. Multi beam Rake receiver.

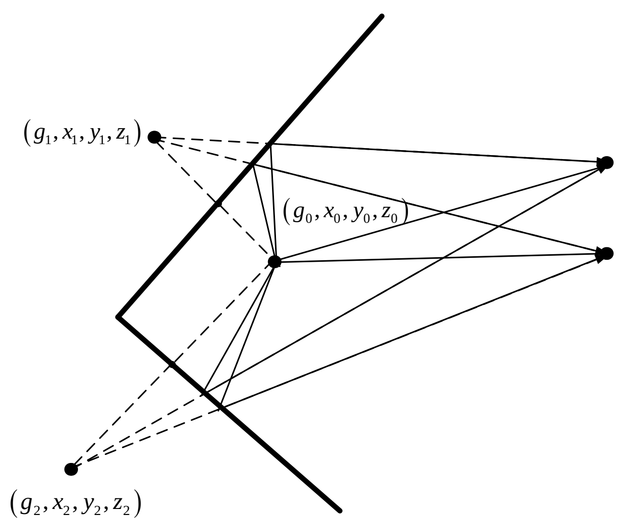

Fig. 18. Multisource channel representation.

In addition to delay and amplitude adjustment of classical Rake receiver, each finger of multi beam Rake receiver is also equipped with a steering engine that provides the matching of finger to beam direction.

We may say that for multi beam Rake receiver, channel estimation boils down to optimal control of Rake receiver fingers in order to provide maximum SNR at the receiver.

The multi beam channel estimation works only for far field where multi beam channel model is applicable. For near field and for distributed M-MIMO, we have to use more general multi-source channel model that was recently presented in [14]. According to this model, a channel is presented as superposition of real and virtual transmitters, as shown in the Fig. 18.

The multisource up and down link channel is given by:

$$h_{UL,m}(t)=\sum_{s=1}^{S} g_{UL,s}\cdot\delta\left(t-\tau_m\left(x_s,y_s,z_s\right)\right) \tag{19}$$

$$h_{DL,m}(t)=\sum_{s=1}^{S} g_{DL,s}\cdot\delta\left(t-\tau_m\left(x_s,y_s,z_s\right)\right) \tag{20}$$

where:

$$\tau_m\left(x_s,y_s,z_s\right)=\frac{\sqrt{\left(x_m-x_s\right)^2+\left(y_m-y_s\right)^2-\left(z_m-z_s\right)^2}}{c} \tag{21}$$

$\left(x_s,y_s,z_s\right)$ is the real and mirror locations of transmitter of antennas.

In multisource approach, instead of a list of spatial parameters of beams $\left(g_s,\alpha_s,\beta_s,\tau_s\right)$ we have to estimate a list of spatial parameters of source s$\left(g_s,x_s,y_s,z_s\right)$.

B.Cost and power consumtion.

Because cost and power consumption of M-MIMO array are proportional to the number of RF chains, the straightforward implementation of M-MIMO is impractical. There are two major approaches to reduce the cost and power consumption:

- Hybrid beamforming [15].
- All digital solution.

The Hybrid and 'All digital' beamforming approaches are illustrated in Fig. and Fig. 20.

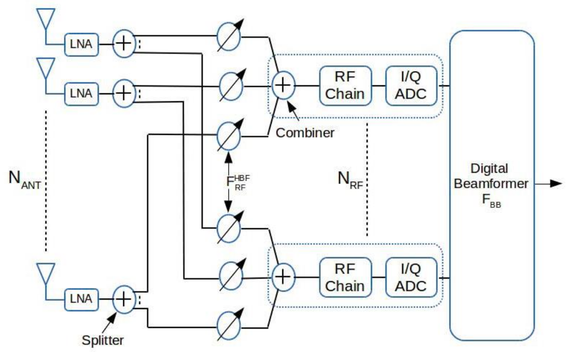

Fig. 19. The hybrid beamforming M-MIMO architecture.

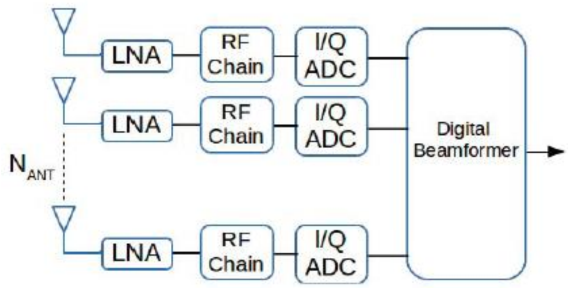

Fig. 20. All digital beamforming M-MIMO architecture.

As we can see from Fig. 19, in the case of hybrid beam forming, each antenna is equipped with a bank of *K* phase shifters that generate *K* analog beams. The number of baseband RF chains and ADC/DAC is equal to the number of analog beams *K*. Because the number of beams *K* is much smaller than the number of antennas *M*, this approach may provide significant reduction of cost and power consumption. However this reduction is not coming for free but at the expense of the following disadvantages:

- The number of beams is limited. This limitation not only limits the number of users that the base station may serve but also reduces the speed of the acquisition of new users, which may be a significant disadvantage for high mobility network.
- This approach works only for array with fixed shape and does not allow conformal array with shape adaptation.

The 'all digital' approach proposes cost and power consumption reduction not by reducing the number of RF chain but by reducing the cost and power consumption of each chain. It is based on the fact that, as we mentioned in the previous chapter, SNR of each RF chain is extremely low. In fact, the noise is so high that relative to it, the ADC quantization noise and the noise that is introduced by low cost RF chain is negligible. The per antenna SNR is so low that we may use very low resolution ADC and very low cost RF chains without significant damage to overall received signal. As for the transmitter, a lower transmit power on each RF chain reduces its linearity requirement and increases the power efficiency of the PA

Despite its limitation and due to its simplicity, the hybrid beamforming technology may be attractive for implementation of low mobility modems with limited number of users, especially for multi backhaul realization. However, despite all the pending challenges, we believe that future belongs to the 'all digital' technology that is rapidly advancing nowadays.

5. Comparison between single and multi carrier modulation for M-MIMO

The major advantage of multi carrier modulation (OFDM) is its resistance to multipath distortion. This important advantage comes at the expense of many significant disadvantages, some are listed below.

- High symbol latency.
- High complexity (FFT).
- Low resistance to nonlinear distortion.
- Low resistance to phase noise.

The M-MIMO is especially sensitive to the three latter problems.

- The high complexity, because the number of FFTs is multiplied by the number of M-MIMO antennas.
- The nonlinear distortion will only grow because in order to reduce cost and power consumption, we want to use cheap components with poor linearity.
- The phase noise will only grow with exploration of new, high frequency band (mmWave).

On the other hand, recent research results show that the problem of multipath is not quite acute for M-MIMO. According to [17], channel delay spread goes down with the growth of the number of antennas in M-MIMO array. Fig. represents Cumulative

Distribution Function (CDF) of post-Maximum-Ratio-Combining (MRC) RMS delay spread as function of the number of antennas for 2.6GHz channel measured by [17].

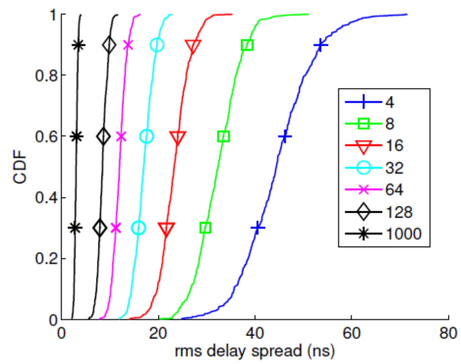

Fig. 21.The CDF of post MRC channel RMS delay spread measured by [17] for 2. 6GHz channel.

The RMS delay spread is defined as:

$$\tau_{RMS}=\sqrt{\frac{\left(\int_{-\infty}^{\infty}P_h(\tau)\cdot\tau^2\cdot d\tau-\int_{-\infty}^{\infty}P_h(\tau)\cdot\tau\cdot d\tau\right)}{\int_{-\infty}^{\infty}P_h(\tau)\cdot d\tau}} \tag{22}$$

where: $P_h(\tau)$ is the power delay profile of the channel,

$h(\tau)$ is the channel impulse response.

$$P_h(\tau)=\int_{-\infty}^{\infty}|E|^2\cdot\Pr\left(|h(\tau)|^2=E\right)\cdot dE \tag{23}$$

Single carrier receiver may operate without equalizer if channel delay spread is much smaller than symbol duration.

$$\tau_{RMS}\ll\frac{1}{BW} \tag{24}$$

For example, the rule of thumb says that single carrier QPSK receiver may operate without equalizer if channel delay spread is smaller than 10 % of symbol duration

$$\tau_{RMS} < 0.1 \cdot \frac{1}{BW} \tag{25}$$

From Fig. 21 we may conclude that the larger the number of MIMO arrays antennas is, the wider the signal bandwidth is that allows the operation of single carrier receiver without the need for equalization.

We analytically proved that the effect of post MRC channel delay spread reduction due to the increase of M-MIMO antennas is explained by the fact that if two multipath beams are sufficiently far from each other, then they are orthogonal. The larger the number of M-MIMO antennas is, the better beams orthogonality is.

$$\lim_{M\to\infty}\left(Cor_M\left(\alpha_1,\beta_1,\alpha_2,\beta_2\right)\right)=0 \tag{26}$$

Where: $Cor_M\left(\alpha_1,\beta_1,\alpha_2,\beta_2\right)$ is the correlation between beam with direction (α_1,β_1) and beam with direction (α_2,β_2)

$$Cor_M\left(\alpha_1,\beta_1,\alpha_2,\beta_2\right)=\frac{\sum_{m=1}^{M} conj\left(Str_m\left(f,\alpha_1,\beta_1\right)\right)\cdot Str_m\left(f,\alpha_2,\beta_2\right)}{M} \tag{27}$$

From beams orthogonality it follows that post MRC channel impulse response converges to Dirac function (LOS channel)

$$\lim_{M\to\infty}\left(\frac{1}{M}\cdot\sum_{m=1}^{M}\int_{-\infty}^{\infty} h_m(\tau)\cdot h_m(\tau-t)\cdot d\tau\right)=\delta(t), \tag{28}$$

where post MRC channel impulse response is given by:

$$H_M(t)=\frac{1}{M}\cdot\sum_{m=1}^{M}\int_{-\infty}^{\infty} h_m(\tau)\cdot h_m(\tau-t)\cdot d\tau \tag{29}$$

The orthogonality of multipath beams in antenna domain makes M-MIMO receiver resistant to multipath distortion.

It means that multi-carrier modulation in case of M-MIMO loses its major benefits and resistance to multipath because M-MIMO itself is resistant to multipath. However, to use multi-carrier modulation we have to pay the price of:

- Latency.
- High complexity.
- Low resistance to non-linear distortion.
- Low resistance to phase noise.

In case of M-MIMO, this price is especially high.

From technical point of view, the above reasoning makes the decision to use M-MIMO single carrier modulation quite obvious.

However, there is one strong argument that advocates for multi carrier modulation: the heritage of previous standards, which companies aim to preserve to minimize new development cost. This one consideration may override all the technical arguments.

However, in our opinion, we should seriously consider single carrier modulation for M-MIMO, as it directly benefits from the larger array size, reduces system cost and power consumption, and offers higher robustness to higher mobility and device nonlinearity.

6. Conclusion

We demonstrated that massive MIMO is a promising technology that offers orders-of-magnitude increase of overall throughput of existing channels and allow the exploration of new high frequency channels. It presents many technical challenges: channel estimation, cost and power consumption reduction, etc. We presented several novel approaches to resolve these problems. We compared two modulation techniques for M-MIMO: single carrier and multicarrier (OFDM) modulations, and came to the conclusion that from the technical point of view, single carrier modulation is preferable. However, due to the heritage of existing standards, we may have to be able to continue support multicarrier modulation.

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