2016 International Conference on Computing, Networking and Communications (ICNC), Invited Symposium

5G Today: Modulation Technique Alternatives

Ender Ayanoglu
Center for Pervasive Communications and Computing
Department of Electrical Engineering and Computer Science
University of California, Irvine
Irvine, CA 92697-2625

***Abstract*—Cellular wireless or mobile communications have seen four generations of technological developments. Today, technologists are proposing a Fifth Generation (5G) for around 2020. Most consider this time to be when the infrastructure will need to be renewed. Together with this observation, it is usually argued that, the new generation technology should possess a number of features. There is no consensus on what these new features should be. Some argue that we are facing a new generation of devices that will have continuous Internet connectivity, and consequently there will be more machine to-machine or machine-type communications. It is argued that machine-type communication will require very low latency. Others argue that the demand for services will increase by about three orders of magnitude and the new technology should be designed to support this tremendous increase, perhaps handling each order of magnitude by means of a different approach. In this paper, we discuss the modulation techniques proposed for 5G and their justification.**

I. INTRODUCTION

Estimates of wireless network traffic by various industry sources all point to exponential increases in traffic. Many sources in industry expect that the wireless cellular traffic volume in a decade will be 1000 times that of today, Some sources specify a traffic increase of 1000 times, although do not necessarily associate a date when this increase will be achieved. At the same time, cellular wireless industry is in the process of developing a vision for its *Fifth Generation* technology (5G). Although what exactly determines 5G is still under investigation and discussion, 1000x capacity increase is generally foreseen as an essential part of this new generation of cellular wireless technology.

Considering that with Long Term Evolution (LTE), and its newer version LTE-Advanced, state-of-the-art techniques from communications engineering have already been standardized, what kind of new technology can go into 5G, together with 1000x capacity increase is an important question. The emerging response from the industry to this question is to divide the need for 1000x capacity increase into three parts: *i)* densification (smaller cells), *ii)* bandwidth and throughput (new spectrum), and *iii)* increase in spectral efficiency (higher throughput in a given bandwidth. It is usually considered that each of these three parts can contribute an order of magnitude improvement and therefore, combining the three, one can achieve an improvement of 1000x. It is noteworthy that *i)-iii)* actually reinforce each other.

A number of researchers argue that 5G is not only about capacity increase. They suggest, due to new applications such as machine-type communications, new criteria in developing new technology are needed. Some of these new applications and the resulting criteria are as follows: *i)* Internet-of-Things: It is anticipated that a very large number of parallel machine-type communications, for example, 100K per cell, will have to be accommodated. This demands very fast access and very low latency from the network. Very fast access implies the possibility of moving away from synchronization of all Remote Terminals (RTs) in a cellular network. *ii)* Gigabit Connectivity: This results in the projected need for 1000x capacity increase. It is caused by a desire for very high speed downloads of large video files, for example. *iii)* Tactile Internet: The Internet is expected to be used by many applications that demand very low latencies such as health care, robotics, vehicle safety, smart city, etc. A common theme among these is the need for a very small response time. It can be shown that a 1 ms application delay requirement translates into a time budget of 100 μs at the physical layer [1]. This is faster than what is possible today. *iv)* Communicating with Multiple Base Stations: Techniques such as Coordinated Multipoint (CoMP) require communication with multiple Radio Base Stations (RBSs) which means synchronism is hard to achieve. As a result, doing away with synchronization altogether is under investigation. *v)* Fragmented Spectrum: It is expected that transmissions may require the use of fragmented spectrum, e.g., white space due to television channels, or carrier aggregation. When this is the case, it is desired that out-of-band transmissions are minimized. This requirement may call for nonorthogonal signaling. *vi)* Energy Efficiency: Cellular wireless networks are highly inefficient. In addition to environmental concerns, this fact makes service providers waste money on operational expenses. It is imperative that 5G incorporate energy efficiency improvements.

In this paper we discuss optimum modulation techniques that can be employed to reach the 1000x capacity increase in 5G. We will discuss all three components specified earlier, with an order of magnitude improvement in each. In doing so, we will keep the criteria *i)-vi)* above in mind. We note that it is possible that there may be different solutions for optimum modulation when small cells are employed versus when large cells are employed, or for conventional cellular wavelengths versus the millimeter wave. It cannot be overemphasized that it is crucial to understand each environment and make the optimum decision accordingly. We will identify the differences in the sequel. Massive MIMO is a technique usually taken

978-1-4673-8579-4/16/$31.00 ©2016 IEEE

under consideration for 5G. It is based on the simple fact that for a large number of antennas N at a base station, simple receiver architectures yield near-optimal performance. The channels for users in distinct locations theoretically become orthogonal and the effect of noise asymptotically vanishes as the size of the array grows [2]. Then, a simple beamformer could achieve both inter-user interference cancellation and noise suppression as $N \to \infty$, provided that the Channel State Information (CSI) for each user is available. The advantages of using more complex approaches based on Zero Forcing (ZF) and Minimum Mean Squared Error (MMSE) have been documented. When N is large, random matrix theory can be employed, simplifying the analysis in a major way. For example, channel matrices that are very tall or very wide are well-conditioned, and methods exist to simplify the inversion of large matrices. These facts make the ZF and MMSE approaches more attractive. Designs such as ZF and MMSE, or other precoder techniques have been studied for large MIMO systems. Pilot contamination can lead to large CSI deviations unless special care is taken involving coordination between adjacent cells.

II. BASIC CONSIDERATIONS

A. Energy Efficiency Implications Based on Modulation

It is well-known that modulated signals with constant-envelope passband signals such as Phase Shift Keying (PSK) can be amplified by using nonlinear Power Amplifiers (PAs). Whereas, if the envelope of the modulated signal is varying, or carrying information, as in the case of Quadrature Amplitude Modulation (QAM), then linear amplification is required. In general, increased variation in the envelope of the signal makes this inefficiency worse. One way of measuring this variation is the Peak-to-Average Power Ratio (PAPR) of the modulated signal.

The implications of a signal with varying amplitude on PAPR are discussed, e.g., [3]. It is known that PAPR with Orthogonal Frequency Division Multiplexing (OFDM) saturates around 12 dB and the resulting PA efficiency is about 20-30%. By improving PAPR, the power efficiency of the PA can be improved substantially. We note that, with Massive MIMO, employing tens or hundreds of antennas each driven by a different PA, the problem can be very severe!

A very important conclusion one should take away from this discussion is that a modulation scheme with constant envelope (PAPR = 1 or 0 dB) is tremendously more energy-efficient than one that has a large PAPR, such as today's OFDM systems with LTE as well as LTE-Advanced.

B. Available Bandwidth

Today, within a band of about 0-5 GHz, there is an enormous amount of data carried over the airwaves. Yet, channels in the millimeter wave (MMW) band (30-300 GHz) offer tremendously more available bandwidth. For example, only within the 60 GHz unlicensed band, 7 GHz of bandwidth is available in the U.S. and Canada, with similar bandwidth being available in Europe, Australia, Korea, and Japan.

This bandwidth is already more than that exists for all of the conventional communication services within 0-5 GHz. Furthermore, O_2 absorption makes propagation in this band restricted to short distances, enabling frequency reuse within a few hundred meters. For this reason, engineering the communication systems for MMW applications may require different approaches compared to conventional communication systems, for which bandwidth was a precious resource. For the purposes of 5G, care should be given to both the conventional cellular wireless (CCW) frequencies ($<$ 5 GHz), as well as the band 5-100 GHz, in particular, to specific MMW bands such as 38 GHz, 60 GHz, or higher.

When there is an abundance of bandwidth, one can trade it off for simplifying the system with a number of different gains. For example, reducing the constellation size while increasing the symbol rate, one could keep the same rate of information in bits per second, but make the signal transmitted have a constant envelope. This has an enormous impact on the power amplifier, energy efficiency, and the cost of the overall system. Although it is clear that these gains are available, a detailed study of these tradeoffs has not been performed yet.

C. Need for Channel Equalization

In a wireless communication system, the received signal has components due to reflections from natural or man-made objects. If the reflections arrive at the receiver with strong amplitude, then they cause what is known as intersymbol interference (ISI). ISI is an impediment to normal reception and it needs to be removed by equalization. Equalization is not a simple process. For Single-Carrier Modulation (SCM), it is performed by adaptive algorithms that employ training sequences and converge to the solution via a number of iterations of their basic steps. This takes a long time, and has not been adopted by the wireless industry, except for narrowband applications. 5G user demands are for broadband services and therefore SCM with adaptive equalization can be ruled out. For broadband applications, there are currently two deployments. Both of these possibilities are employed in the Fourth Generation cellular wireless standard LTE, one in the downlink and the other in the uplink. Both are based on OFDM. In LTE, OFDM is employed in the downlink. In the uplink, due to a desire to eliminate expensive power amplifiers because of the high PAPR of OFDM, SCM is employed, but equalization is performed in the frequency domain. The way frequency domain equalization of SCM is performed makes the implementation similar to OFDM, with a number of additional hardware blocks inserted into a conventional implementation of OFDM. This is known as Single-Carrier Frequency Multiple Division Multiple Access (SC-FDMA). The block diagrams for OFDM and SC-FDMA, explicitly displaying which blocks are added to OFDM to implement SC-FDMA are given in Fig. 1.

The advantages of frequency domain equalization, both for OFDM and SC-FDMA, over adaptive equalization for SCM have been well-documented. Elimination of detailed equalization for an MMW system can be a good goal, with

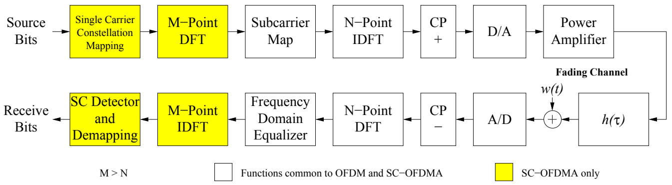

Fig. 1. Block diagrams for OFDM and SC-FDMA.

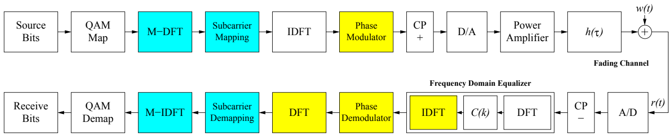

Fig. 2. Baseband block diagram of CE-SC-FDMA. Yellow-shaded blocks are added to conventional OFDM to result in CE-OFDM. Cyan-shaded blocks are added to CE-OFDM to result in CE-CS-FDMA.

perhaps performing a coarse equalization only. It is common to categorize propagation channels as being Line-of-Sight (LOS) or Non-Line-of-Sight (NLOS). While an NLOS channel requires substantial equalization, an LOS channel may need no or only a coarse equalization. Due to their specific propagation conditions, the MMW channels are usually characterized as being LOS. Similar behavior can be expected in small cells at CCW frequencies. As a result, it is plausible that we may not need equalization for MMW frequencies or small cells. If that is the case, neither OFDM nor SC-FDMA may be needed and an SCM technique may be sufficient. The advantages of this are the elimination of DFT and IDFT operations, and also, the elimination of the cyclic prefix and pilot subcarrier overhead.

III. PROPOSED MODULATION TECHNIQUES

Our goal in this paper is to point to the importance to investigate and develop a modulation technique that can be employed in 5G cellular wireless communications with the capability of supporting 1000x capacity increase by employing Massive MIMO, CCW or MMW frequencies, and/or small cells, while at the same time emphasizing energy efficiency and to satisfy the needs of low latency, and potentially, asynchronous transmissions and nonorthogonal signaling. In addition, it is desirable to understand the optimal solution when Massive MIMO or small cells are not present.

A. *Constant-Envelope Single-Carrier Modulation*

As discussed in Section II-A, a modulation technique with constant envelope, or constant amplitude, will simplify the final stage of the transmitter, reduce its cost, and increase the energy efficiency of the overall system. It is possible to implement such a signal by a number of different approaches. The first is a conventional one and will be briefly discussed in this subsection. The others are new approaches, and will be discussed later in this section. In all cases, there are a number of tradeoffs, the most prominent of which is the bandwidth expansion. The bandwidth expansion can be easily tolerated due to the abundant bandwidth available in MMW bands or due to a network of small cells. We reiterate that small cells achieve major frequency reuse and thus are an important way to enhance spectrum use.

Since the 1970s that the best choice for the RF amplifier in many applications is a nonlinear one, and it is preferable to drive it with a constant-envelope signal. It was also determined that if the modulated signal has continuous phase, it can tolerate the nonlinear distortion introduced by this amplifier. These signals have been studied in substantial detail in the literature, uunder the general title of Continuous Phase Modulation (CPM). One version of this class of signals, known as Minimum Shift Keying (MSK), is employed in the Third Generation cellular wireless system Global System for Mobile Communications (GSM). MSK has well-documented advantages. Investigation of M-ary CPM is a very interesting research direction but very little work exists in this area.

A detailed study of constant-envelope SCM in small cell applications at CCW or MMW frequencies both with Massive MIMO and without is a worthwhile undertaking. CPM formats have been around for a long time, whether they may be the optimum techniques in use for some specific scenarios in 5G is an important research question for today because 5G brings about a number of new constraints which may revitalize these modulation formats.

B. *Constant-Envelope OFDM*

While due to its large PAPR values, OFDM is highly wasteful of power, it is possible to come up with a version of OFDM that has constant envelope (or constant amplitude). Fig. 2 can be used to understand Constant-Envelope OFDM (CE-OFDM). In this figure, unshaded blocks constitute an OFDM system. Yellow-shaded (light-shaded) blocks can be added to make a CE-OFDM system. For the time being, ignore the cyan-shaded (dark-shaded) blocks in this figure. In this uncoded version, the source bits are mapped through QAM modulation to generate a complex-valued sequence $X[k]$ of QAM constellation points. A conjugate symmetric version of this sequence is generated, which, after going through an Inverse Discrete Fourier Transform (IDFT) block, generates a real-valued sequence $s[n] = \exp(jCx[n])$, where C is a scaling constant and $j = \sqrt{-1}$.

The members of the sequence $X[k]$ entering the IDFT are from a finite alphabet of QAM symbols. After the IDFT, the OFDM sequence $x[n]$ has varying magnitudes. However, after the transformation $s[n] = \exp(jCx[n])$ by the phase modulator, the complex-valued sequence $s[n]$ has unit magnitude. The information content is transformed into the phase of $s[n]$. The sequence $x[n]$ has large PAPR, whereas the sequence $s[n]$ has 0 dB, or no PAPR.

It has been shown via simulations that CE-OFDM has better Bit Error Rate (BER) performance than OFDM when used with realistic power amplifier models and with realistic backoff values for OFDM in additive white Gaussian noise (AWGN) and fading channels. Also, it has been shown that CE-OFDM has better fractional out-of-band power as compared to OFDM. CE-OFDM is certainly promising. But, more work needs to be done regarding understanding its bandwidth tradeoff, phase unwrapping performance in the presence of noise, performance in the presence of coding, and the tradeoffs against conventional methods to remedy PAPR.

C. Constant-Envelope Single-Carrier FDMA

It is possible to combine the technique of SC-FDMA with CE-OFDM, as shown in Fig. 2. This technique is termed Constant-Envelope Single-Carrier FDMA (CE-SC-FDMA). The motivation of CE-SC-FDMA is the fact that SC-FDMA exhibits lower envelope fluctuations than OFDM. As a result, the variance of the phase-modulated signal is reduced. This results in the expectation that the amount of degradation suffered by the nonlinear transformation is reduced as well.

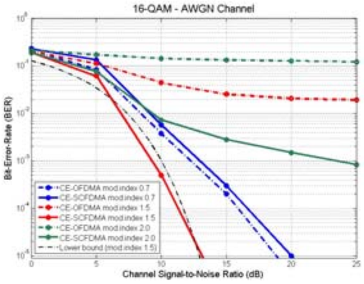

Fig. 3. Performance of CE-SC-FDMA against CE-OFDM in AWGN channel.

CE-SC-FDMA was introduced in [4] for nonlinear satellite channels. There are a number of simulations performed, which we will discuss below. Fig. 3 shows the performance of CE-SC-FDMA against that of CE-OFDM in an additive White Gaussian noise (AWGN) channel for different values of the phase modulation index, specified as $2\pi h = 0.7$, 1.5, and 2. The best result for CE-OFDM is obtained for $2\pi h = 0.7$ while that for CE-SC-FDMA is obtained for $2\pi h = 1.5$. We note from this figure that at a Bit Error Rate (BER) of 10^{-5}, the best CE-SC-FDMA configuration beats the best CE-OFDM configuration by about 6 dB in terms of the channel Signal-to-Noise Ratio on the AWGN channel with 16-QAM on each subcarrier. As in the case of CE-OFDM, the aspects of phase noise, bandwidth expansion, and performance under channel coding are open problems that need to be investigated [4]. In addition, performance on propagation channels peculiar to Massive MIMO together with PA models applicable to such channels need to be investigated.

A number of tradeoffs exist with CE-SC-FDMA. First, the computational complexity increases due to the oversampling needed to generate the data sequence with the particular characteristics, as in the case of CE-OFDM. A second source of computational increase is due to the additional DFT-IDFT pair on top of CE-OFDM. The computational complexity increase may add to an increase in energy consumption and therefore energy efficiency, and therefore its net effect needs to be investigated. The second tradeoff is shared with CE-OFDM and is the reduced spectral efficiency to generate the particular real-valued waveform. However, the presence of smaller cells or MMW bands may actually reduce the importance of this reduction. More importantly, the Massive MIMO technique actually enables a huge increase in spectral efficiency and as a result, the net effect on spectral efficiency will still be substantial.

D. Non-Orthogonal Multiple Access (NOMA)

A technique introduced by DoCoMo for radio access, called Non-Orthogonal Multiple Access (NOMA) has received significant attention In addition to DoCoMo, it appears to have been embraced by Intel and China Mobile. The technique can be based on conventional OFDMA or DFT-spread OFDM. The basic idea is to do away with the use of orthogonalizing the spectrum for different users, and instead, allocating the same spectrum to different users. The data destined for each user is extracted by using Successive Interference Cancellation (SIC).

In addition, Hybrid Automatic Repeat Request (HARQ) is employed to improve performance. Significant gains for the total user rate (almost twice) are reported, as shown in Fig. 4. However, once again, these gains are minor as compared to what can be achieved with Massive MIMO.

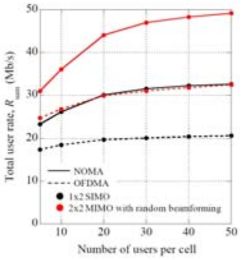

Fig. 4. NOMA rate gain.

E. 5GNOW Project

5GNOW is a project being carried out under the auspices of the European Commission Seventh Framework Programme (FP7). The main premise of the project is based on questioning the assumptions present in LTE and LTE-Advanced. These are questions based on *i)* the difficulty of synchronizing machine-type communications, *ii)* the difficulty of achieving synchronicity and orthogonality with Coordinated Multipoint (CoMP), a scheme in which an RT talks to multiple, coordinating RBSs, and *iii)* the ability to address noncontiguous spectra such as that would be needed in the case of white space communications, e.g., cognitive radio or the carrier aggregation technique already being considered for 4G. Different members of the consortium have produced different modulation proposals, with a number of commonalities yet some differences. There are four such proposals: Frequency Bank Multicarrier (FBMC), Generalized Frequency Division Multiplexing (GFDM), Universal Filtered Multicarrier (UFMC), and Biorthogonal Frequency Division Multiplexing (BFDM). The basic idea in all of these techniques is the fact that a multicarrier modulation system can be implemented by employing filter banks to divide the data to be transmitted into different bands. OFDM happens to be a special case of this interpretation. It is important to realize that by changing the filter banks, it is possible to change the characteristics of transmission and address the issues of synchronization, nonorthogonality, and out-of-band spectra discussed in *i)-iii)* above. GFDM, UFMC, and BFDM are variations of FBMC. The differences in the case of UFMC and BFDM are minor. On the other hand, GFDM employs frequency domain equalization, and therefore has a Cyclic Prefix (CP), whereas FBMC avoids CP to reduce the overhead, but uses more complicated equalization. In general, throughput, BER, and PAPR performance of these techniques are close to that of OFDM, with improvement in terms of the issues specified in *i)-iii)* above. Because the performance of UFMC and BFDM

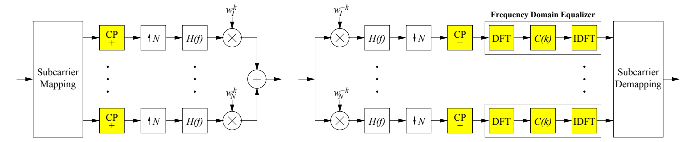

Fig. 5. Baseband block diagram of GFDM modulator (left) and demodulator (right), $w_i = e^{j2\pi f_i}, i = 1, 2, \ldots, N$. FBMC avoids shaded blocks CP+ and CP-, and the frequency domain equalizer with DFT, $C(k)$, and IDFT. Note $C(k)$ is a simple one-tap equalizer.

over that of FBMC are not significant, in this family, one can concentrate on FBMC and GFDM, with their choices of time-domain versus frequency-domain equalization, respectively. We note that FBMC is proposed as one of the three potential modulation formats for 5G. A block diagram of GFDM is given in Fig. 5 which can be employed to visualize the block diagram of FBMC by omitting the blocks for the cyclic prefix insertion and deletion, and frequency domain equalization.

F. *Frequency Quadrature Amplitude Modulation (FQAM)*

This technique is proposed by Samsung. It is a combination of FSK and QAM where a QAM alphabet is employed at a different frequency which is chosen judiciously in order to combat Inter-Cell Interference (ICI). Their proposal achieves 2-3 times higher transmission rates at the cell edge, depending on the cellular configuration. Although the cell edge user rate increase of 2-3 times is moderately significant, Massive MIMO can be expected to generate a narrow beam and as a result, the problem of ICI will decrease substantially due to its use. Finally, and most importantly, FQAM with a general QAM alphabet (e.g., 16-QAM or 64-QAM) is not a constant-envelope modulation technique. It will have a considerable PAPR and will require significant backoff.

G. *Techniques for RF Beam Switching*

Due to the need for supporting multiple users in 5G, it is desired to be able to switch RF beams from one user to another in a short time, e.g., in the downlink. In OFDM, this requires an extra null period of no transmission and therefore presents an overhead. Two techniques have been proposed to overcome this overhead. The first is called Null Cyclic Prefix Single Carrier (NCP-SC). The second is a variation of OFDM, and is called Zero-Tail Spread OFDM (ZT-OFDM). NCP-SC has somewhat lower, but not negligible PAPR performance in its BPSK and QPSK versions, while its 16-QAM PAPR performance is quite high. On the other hand, ZT-SOFDM has quite significant PAPR performance. As discussed earlier, for our purposes, nonzero dB PAPR performance can be considered, but is not preferred. On the other hand, due to much higher transmission rates and spectral efficiency achievable via Massive MIMO, the importance of a guard interval stemming from RF beam switching may not be very important.

H. *Time-Frequency-Packed Signaling (TFS)*

This modulation format is a generalization of the concept of faster-than-Nyquist signaling. In faster-than-Nyquist signaling, the transmission rate is more than the strictly bandlimited channel would allow for transmission without interference. Therefore, some intersymbol interference results but it is removed by processing at the receiver side. It is known that some modest increase in transmission rate can be achieved by this means. In TFS, this one-dimensional concept is generalized into two dimensions of time and frequency. The resulting system is a generalization of FBMC. TFS has only modest increases in throughput over FBMC.

I. *Spatial Modulation*

TABLE I
SPATIAL MUX MAP

2 TX, QPSK		
Bits	Antenna	Symbol
000	1	+1+j
001	1	-1+j
010	1	-1-j
011	1	+1-j
100	2	+1+j
101	2	-1+j
110	2	-1-j
111	2	+1-j

Spatial modulation is a new version of MIMO where there are multiple transmit antennas, but only a number of them (typically one) is active at a given time. Due to the availability of the degrees of freedom in a MIMO channel of sufficiently many receive antennas, for a given transmission, the receiver can determine which of the transmit antennas were active. Therefore, the index of the transmit antenna employed carries information, in addition to the symbol that was transmitted from the active antenna, as shown in a simple example in Table I. Although the basic idea is very simple, spatial modulation performs surprisingly well. In particular, a study reported in 2014 has shown that in the same setting and in an uplink scenario, spatial modulation can beat Massive MIMO by several dBs in BER performance [5]. This configuration has only one RF chain at the RT, but employs a number of different antennas, only one of which is active at a given time. Note that this is different than antenna switching since in this case, unlike antenna switching, which antenna is active carries part of the information. With this approach, multiple RF chains at the RT can be avoided.

IV. CONCLUSION

This paper is on a set of new modulation techniques that can be employed in next-generation cellular networks, or 5G. The community is facing a set of new set of modulation techniques. It is possible to argue that new ones will come along. Next few years will see a comparison to determine the best best modulation technique, or techniques, under the emerging paradigm of 5G.

REFERENCES

[1] G. Wunder *et al.*, “5GNOW: Non-orthogonal, asynchronous waveforms for future mobile applications,” *IEEE Communications Magazine*, vol. 52, pp. 97–105, February 2014.

[2] T. Marzetta, “Noncooperative cellular wireless with unlimited numbers of base station antennas,” *IEEE Trans. Wireless Comm.*, vol. 9, pp. 3590–3600, September 2010.

[3] K. Davaslioglu and E. Ayanoglu, “Quantifying potential energy efficiency gain in green cellular wireless networks,” *IEEE Communications Surveys and Tutorials*, vol. 16, pp. 2065–2091, Fourth Quarter 2014.

[4] R. Mulinde, T. F. Rahman, and C. Sacchi, “Constant envelope SC-FDMA for nonlinear satellite channels,” in *Proc. IEEE GLOBECOM 2013*, December 2013, pp. 2961–2966.

[5] T. Narasimhan, P. Raviteja, and A. Chockalingam, “Large-scale multiuser SM-MIMO versus Massive MIMO,” in *Proc. Information Theory and Applications Workshop*, February 2014, pp. 1–9.