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Going Toward 6G

The cellular industry has just reached another milestone with the development of 5G wireless communication technology. While research in 5G is a core part of the Signal Processing for Communications and Networking (SPCOM) technical committee, it may also be found in several other technical areas. As this is also my core expertise, I have decided to discuss, in this editorial, the expected goals that 5G has and has not achieved and what might be coming in 6G cellular networks.

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Cellular communication systems are constantly evolving, with new releases every one to two years. Roughly every 10 years, one of the releases is branded as a *new generation*. Usually, the new generation standard has been designed to achieve some significant performance improvements. Two of the differentiating areas of 5G are illustrated in Figure 1. The "5G flower" is shown in Figure 1(a). It indicates the different performance objectives that might be achieved by a 5G link. Of course, they are conflicting and cannot be optimized simultaneously, e.g. low latency, high mobility, and high data rates may not be possible at the same time. Figure 1(b) shows some of the key industry verticals. Many different industries have made use of cellular communication in the past, but 5G also considered the requirements of devices associated to the different verticals. From an automobile to a smart meter or an industrial robot. A main motivation for looking at applications of cellular beyond wireless Internet access is alternative revenue sources. To meet the different requirements for new devices, changes are made in all aspects of the cellular system, including the

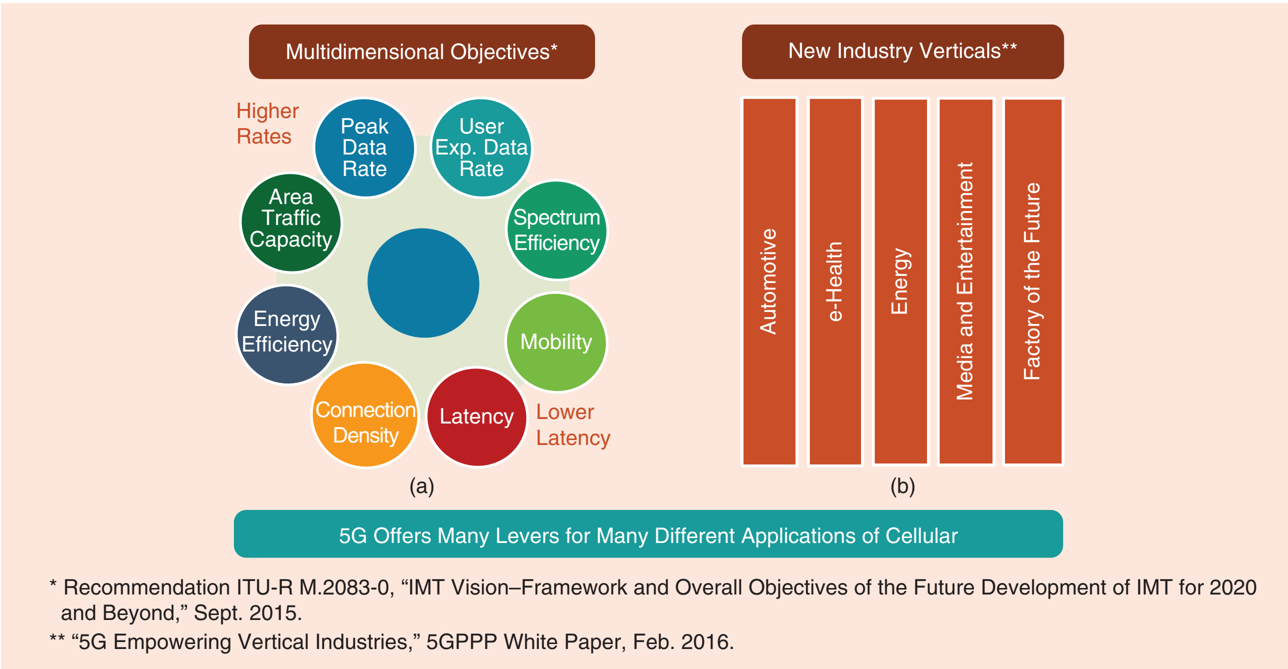

FIGURE 1. Key features that motivated the development of 5G. (a) The multidimensional objectives, essentially the different benefits that 5G might offer. (b) Some of the driving industry verticals. (Figure created by and used with permission of Nuria Gonzalez Prelcic.)

physical layer waveforms and the higher layer networking.

In this editorial I also describe three promising directions for 6G, building on observations about limitations of 5G. First, I summarize how the physical layer needs to support higher bandwidths, higher carriers, yet at lower powers. Second, I describe how the industry verticals from Figure 1(b) were not completely served and how 6G may be designed around these areas. Finally, I highlight the potential role that machine learning may play in 6G in a more integrated fashion than done before.

At the physical layer, one of the differentiating features of 5G is the use of the millimeter-wave spectrum. The reason to go to carrier frequencies around 28 GHz and above (versus the usual cellular frequencies in the 1 GHz or 2 GHz range), is the potential for higher bandwidth communication channels. In current cellular systems, bandwidths of 5–20 MHz are common, with up to 100 MHz possible using some tricks like carrier aggregation. In contrast, 5G may support 400 MHz of bandwidth at millimeter-wave channels. With larger bandwidths, the data rates are proportionally higher. While impressive, 6G has the potential to do better.

I see three areas of opportunity for 6G in physical layer research. One opportunity is going to higher carrier frequencies above 40 GHz, including even the terahertz bands. This will make spectral channels with bandwidths of several gigahertz to tens of gigahertz possible. The second opportunity is the support of low-resolution multiple antenna architectures. By reducing the resolutions of the analog-to-digital and digital-to-analog converters to as little as 1 bit, it may become practical to process those higher bandwidth channels with lower power consumption. An additional advantage of low-resolution architectures is the higher flexibility offered by using digital beamforming architectures to support multiple users. The third opportunity is to re-investigate large bandwidths in the context of signal processing models. Most models used in SPCOM research make a narrow-band assumption, which starts to be violated for large bandwidths or large array apertures. Including more electromagnetics and circuits back into these models may lead to new algorithms and communication insights, for example, to develop very large and yet wideband arrays for multiple-input, multiple-output (MIMO) communication. In essence, going to higher carriers, larger bandwidths entail better models for hardware and impairments. This will, in turn, lead to new models for the theory, which will be essential for 6G.

While I am excited by the new industry verticals shown in Figure 1(b), I do not believe they have been adequately addressed by 5G. For example, most of the focus on millimeter wave for 5G and its early trials was on broadband wireless to the home (as an alternative to cable or fiber). The initial large-scale deployments will also include millimeter-wave capability in handsets. I do not think that enough work was put into the industry verticals. For example, work on 5G for automotive applications has just started in earnest. It seems reasonable to conclude that the beam-based architecture as part of 5G will not likely support high mobility automotive applications. As a result, I believe that the automotive vertical remains one of three areas of opportunity in industry verticals that will be addressed by 6G. There is no reason that the focus should just be placed on ground vehicles. Aerial vehicles are now poised to play a larger role in society including for monitoring, package delivery, and personal transport. Therefore, a second opportunity lies in the aerial vertical for 6G. Finally, robotics is a significant use case of signal processing as found in the factory of the future. While 5G includes some support for wireless aspects for robotics, e.g., low latency, it was not designed for the diverse set of all positive robotic applications, especially in personal robotics. As a result, I believe robotics is the third area of opportunity in the industry verticals for 6G. In essence, I see the potential for many signal processing–heavy industry verticals to influence the development of 6G.

A third key direction for 6G research is in the applications of the machine-learning toolset. There are many areas of functionality in 5G, which are not explicitly standardized, that could use machine learning immediately. Examples here include functions like user scheduling or handoff. To get the most gains from machine learning though, I believe that one opportunity for 6G is to incorporate the right "hooks" to facilitate the exchange of data and models required. For example, transfer learning might be useful to convey models learned in one cell to another cell, while end-to-end learning may be helpful for dealing with physical layer modeling mismatches and nonlinearites. A second opportunity for applying machine learning to 6G is to develop a means for collecting large and relevant data sets. This is an essential part of the design and evaluation process during standard creation. It is too late to collect the data when the standard is already designed. A third opportunity in the application of machine learning for 6G is to exploit the wealth of sensor data. Base stations may contain collections of sensors beyond communication, for example, cameras, LIDAR, or radar to help support automated driving. This information could be used as side information to improve the communication link. This requires incorporating the right "hooks" in the system and algorithms as well as developing multisensor simulation methodologies that are industry vertical specific to facilitate testing. This means that signal processing, under the guise of machine learning, may play a leading role in 6G—more than all of the previous generations of cellular technology.

I hope that you can see the potential for signal processing in each of the areas that I have outlined. From my perspective, our work in diverse areas of signal processing have the chance for significant impact on 6G and society at large. Maybe now is the time to have a special issue of *IEEE Signal Processing Magazine* on the topic of beyond 5G communications. Any volunteers?