EE6143: Advanced Topics in Communications
Assignment 1: 4G and 5G – Common Technology Features and Key Differences

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1 Introduction

1.1 4G

4G is the *Fourth Generation* of broadband cellular network technology. It primarily relies on the *LTE (long-term evolution)* standard for cellular broadband communication developed by *3GPP (Third-Generation Partnership Project)*. For technology to be considered 4G, it needs to adhere to the *IMT Advanced Standard*.

Most of the technology initially marked as 4G didn't actually fall under the 4G specification by IMT and couldn't technically be considered 4G, but are branded as 4G by ISPs (internet service providers).

The key idealogies and goals of 4G are as follows:

- Offering faster data download and upload speeds compared to 3G with high mobility
- Reduced latency, resulting in more responsive user experiences
- Enhanced network capacity allowing more simultaneous connections
- Use of MIMO (Multiple Input Multiple Output) and beamforming for better signal quality and improved spectral efficiency

1.2 5G

5G is the *Fifth Generation* technology standard for broadband cellular networks and is the successor to 4G. The aim of 5G is for"everyone, everywhere, everything" to be connected. 5G primarily consists of three use cases:

- eMBB: enhanced Mobile Broadband Communication
- mMTC: massive Machine-Type Communication
- URLLC: Ultra-Reliable and Low-Latency Communication

The primary differences are summarized below in figure 1 [3]:

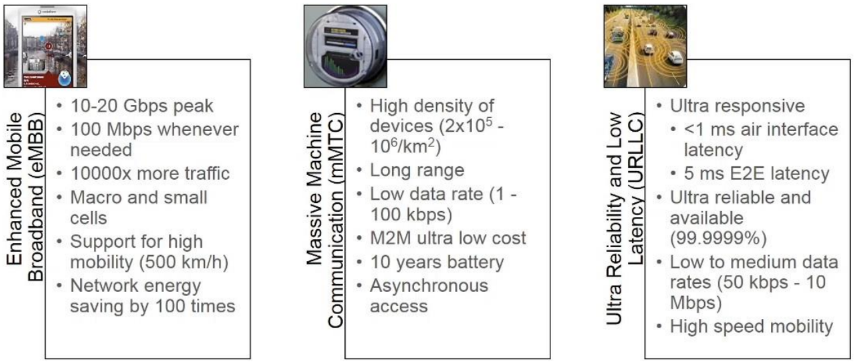

Figure 1: Fundamental use cases of 5G

2 Requirement Differences

In terms of around seven different parameters, 5G specifications are more stringent than their corresponding 4G equivalents. This is depicted in 2:

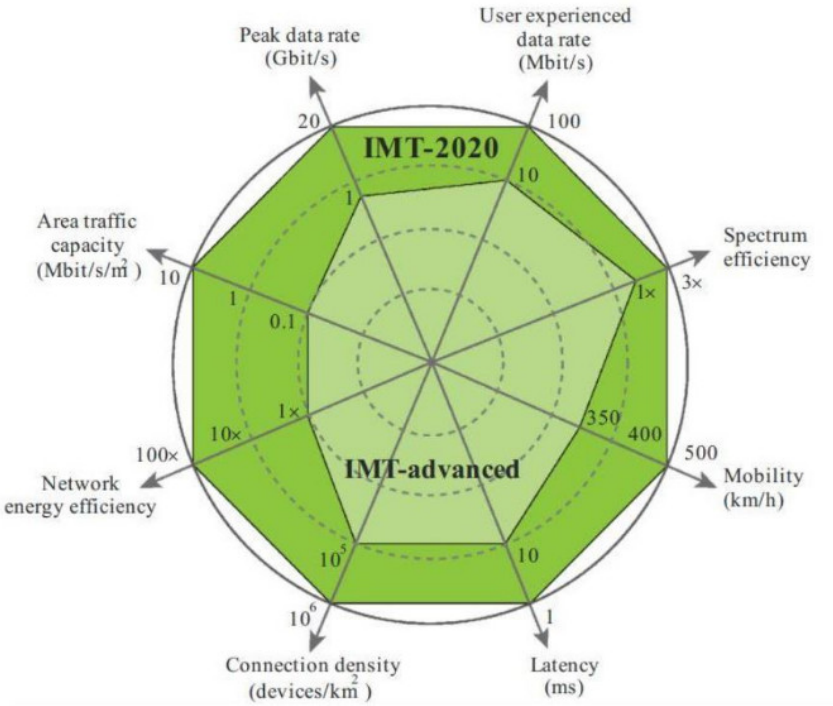

Figure 2: 4G (IMT-advanced) vs 5G (IMT-2020) comparison

3 Core Infrastructure

4G consists of a core network, with advanced specifications utilizing an EPC (*Evolved Packet Core*) [4]. EPC is required for more advanced LTE applications like VoIP (voice over IP) and so on.

There are two primary modes of developing 5G infrastructure [2]:

- **NSA (Non-Standalone) architecture:** Utilization of 4G for the data and control plane and utilization of 5G only for the data plane. The core network can be *EPC* in this case.

- **SA (Standalone) architecture:** Utilizes a new 5G core called NGC (*next-generation core*), and 5G everywhere

Currently, NSA is preferred due to easier deployability, but in the long run, SA architecture will be ideal.

3.1 5G NGC

Below are some of the features from 5G NGC [2]:

- Configurable end-to-end connectivity per vertical
- Modular, specialized network functions per service
- Flexible subscription models
- Dynamic control and user planes with more functionality at the edge

4 Frequencies Used

In LTE (4G), there is support for frequencies upto 6 GHz [4].

In 5G however, there is support for frequencies upto 52.6 GHz [5] (and higher frequency support is in progress [8]). This is the so-called *mm-wave* (millimeter wave) band. Higher frequencies get attenuated easily, so 5G plans to rely on both lower ($\sim$ 3 GHz) and higher frequencies ($\sim$ 30 GHz). Higher frequencies will be used for high-speed internet with lesser coverage, while lower frequencies will be used to maximize coverage.

5 Beamforming and MIMO

A key development in 4G is the usage of *multiple antennae single-user MIMO* (multiple-input multiple-output) system. The precoder matrix is determined by a closed-loop (feedback) system. There is support for *beamforming* also, although the beamforming is spatial and can be in accordance only to a predefined set of vectors.

5G takes this to the next level: at a higher frequency, there is a need to transmit at a greater power to increase coverage. To achieve this, we use *analog beamforming* [5]. Beamforming has the disadvantage that we can transmit only in one direction at a given time, so *beam sweeping* is required to reach the entire coverage area. At lower frequencies, there is support for *multi-user MIMO*: we separate users spatially and send signals. For this however, the base-station needs to know CSI (channel state information), which we achieve by CSI feedback from the users [9].

MATLAB tools can be used for simulating and testing these use-cases [1].

6 Ultra-lean design

LTE base-stations send some signals which are “always-on”: such as the signals for base-station detection, channel estimation, and so on [5]. This can be considered a waste of energy. 5G prioritizes on an ultra-lean design: minimizing always-on transmissions and minimizing signal monitoring, thereby making the system more *energy efficient*.

5G achieves this in the following manner:

- Reduced signal monitoring in low-mobility situations [8].
- Formulation of RedCap UE (Reduced Capability User Equipment) devices which have lesser antenna branches, and half-duplex operation [8].

7 Multiple-access

Orthogonal multiple-access (OMA) is a cornerstone of cellular technology. In 2G we have FDMA (frequency-division multiple access), in 3G we have TDMA (time-division multiple access, and in LTE we have CDMA (code-division multiple access). OMA signals are easy to encode and decode and can be done with low-complexity devices [6]. OFDMA (orthogonal frequency-division multiple access) is a cornerstone of 4G/LTE [7]. 5G also utilizes OFDM (orthogonal frequency division multiplexing).

The number of orthogonal channels available is highly limited. With improvements in computing power, 5G attempts to incorporate Non-orthogonal multiple access (NOMA). The primary focus is on power-domain NOMA.

7.1 Power-domain downlink NOMA

From the base station, we attempt to transmit two signals x_1 with power P_1 and x_2 with power P_2 to two users (user 1 and user 2 respectively). Thus, the transmitted signal s is $s = \sqrt{P_1}x_1 + \sqrt{P_2}x_2$. In our model, the sum $(P_1 + P_2)$ which is the power sent by the base station is fixed, but we get to choose the relative powers for the two users.

The signal received at user 1 is $y_1 = h_1 s + n_1$, where h_1 is the channel gain and n_1 is some Gaussian noise with spectral power density $N_{f,1}$. Likewise, the signal at user 2 is $y_2 = h_2 s + n_2$, where n_2 is Gaussian noise with spectral power density $N_{f,2}$.

Let's call user 1 a "strong" user and user 2 a "weak" user, i.e. $\frac{|h_1|^2}{N_{f,1}} > \frac{|h_2|^2}{N_{f,2}}$.

We pick powers such that the stronger user gets less power and the weaker user gets more power to improve the SINR (signal to interference-plus-noise ratio). In conclusion, we pick $P_1 < P_2$.

Let the channel capacities (data rates) be R_1 and R_2 for user 1 and user 2 respectively. We'll attempt to characterize these rates now.

At user 2, it's easy to decode: we decode it naively, since it has greater SINR anyways. The rate R_2 we obtain is:

$$R_2 = \log_2\left(1 + \frac{P_2|h_2|^2}{P_1|h_2|^2 + N_{f,1}}\right)$$

Note: Channel capacity of AWGN channel is $\log_2(1 + SINR)$.

At user 1, we perform SIC (successive interference cancellation). We first decode x_2 (the signal of user 2), then subtract it from the received signal y_1, after which it decodes its own signal. Now, note that there is no interferer in the SINR expression here, that is because we've removed it already when we performed SIC. The rate R_1 obtained is:

$$R_1 = \log_2\left(1 + \frac{P_1|h_1|^2}{N_{f,1}}\right)$$

By adjusting the relative ratios of P_1 and P_2, we can improve the performance immensely, as shown in the graph 3.

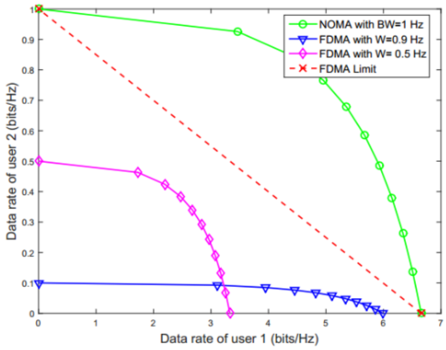

Figure 3: Data rates in OMA vs NOMA [6]

This same *trick* can be extended to N users, and we'd have a lot more data rate than the naive OMA. However, imperfect SIC (successive interference cancellation) does lower the effectiveness of NOMA and it is usually much harder to implement in practice.

8 Data-driven approach with AI/ML techniques

LTE does have some support for "data analysis", but this is very classical in the form of channel estimation.

In contrast, several features of 5G (in Rel-17 and Rel-18) are focused on a *data-driven approach*: using artificial intelligence and machine learning techniques to solve optimization problems [8].

5G signals are generated, captured and stored, and can be used by test engineers to test the proper working of the 5G systems. This can be done by MATLAB tools [1].

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