DOI. No. 10.13052/2794-7254.028

# Pragmatic 6G

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Cellular communication is the backbone of our digital society. Today's excitement around AI is a result of the whole planet having access to newest developments instantaneously via the mobile Internet. However, the cellular industry is currently not in a good shape. It therefore is time to wake-up and draw a picture of opportunities ahead that could make 6G a real game changer.

This paper is not about presenting math, or a technically detailed vision about technologies that might enter the 6G standard as e.g. [1]. It is about presenting a vision and roadmap towards a possibly amazing future of the cellular industry.

## The Situation Room

Every generation of cellular communications has given us a chance to move ideas into reality, creating innovations that are the basis of our modern life. Now we are at the doorstep of defining 6G, which again poses the chance to write a new chapter of technology benefits for humankind.

However, the cellular world is in a mode of crisis, as can be seen by analyzing the stock charts of public companies involved. On a 20-year timeline, no operator and no equipment manufacturer is performing at the S&P 500 level, but all are well below. The market cap of publicly listed equipment manufacturers has even been trending negative in absolute numbers. As a generation of cellular technology has entered the market roughly every 10 years, this means that the industry has not overcome the Y2K bubble and remains in post-3G hangover. At the same time the world has become more and more dependent on the cellular infrastructure. We desperately need a new silver lining to revive the industry. Cellular is the backbone of our modern life.

5G was driven by three main needs:

1. Increasing bandwidth to address the traffic growth as seen during 4G
2. Reducing the latency, creating an ultra-reliable low-latency (URLLC) network slicing architecture, to address the "Tactile Internet" [2] requirements of motion control of real (robots) and virtual objects (XR)
3. Implementing massive machine type communications (mMTC) for an Internet-of-Things (IoT) use case envisioned

The reality has come to face the following.

1. Bandwidth is currently hardly increasing anymore, i.e. the assumption of an ever-increasing explosion of traffic bandwidth is false, at least as of now (2025/26). Growth is slow at 20% per year. Traffic volume has nearly come to a halt.
2. Each odd generation of cellular introduced a new service, namely 1G introduced mobile telephony, and 3G mobile Internet, respectively. These new services were initially successful for business customers. You might remember that 1G was a business phone, and 3G was either a Blackberry or Nokia Communicator, clearly addressing the business needs. In case of 5G, the new Tactile Internet service via URLLC was tried out by many businesses in so-called campus or private mobile networks (PMN); this, in many cases, turned out to be way too complex for running a PMN. The wide area applications, such as autonomous driving, have only been successful use cases in niche markets, e.g., for moving outdoor AGVs (automatic guided vehicles).
3. In 5G, the evolution of low-power massive IoT builds directly on 4G's NB-IoT and LTE-M. This is realized within 5G New Radio through the mMTC service class, while RedCap (Reduced Capability, also known as NR-Light) addresses medium-complexity IoT use cases. NB-IoT and LTE-M remain supported and continue to evolve within the 5G ecosystem. Rather than introducing a single new IoT technology, 5G integrates these approaches, with RedCap bridging the gap to more capable IoT devices. Neither was a truly low-power IoT system standardized nor was RedCap available soon enough to build-up momentum so far.

**It is therefore time to revisit the 6G vision [3] and update this at a high level.**

## 6G's Profit & Loss Approach

Every company has to publish its profit & loss statement (P&L). The top-line shows the revenue sources, the bottom-line the profit. Achieving higher profits can be done either by increasing the top line without dramatically increasing the costs, or by reducing the costs to improve the bottom-line.

Taking current cellular industry's situation, we desperately have to concentrate on the P&L. What are new sources of revenue, and what are possibilities to reduce cost? Reducing cost of an operator at the cost of reducing its infrastructure equipment expenses makes operators happy, but destroys the future of vendors. This sounds like a less promising idea for recreating a vibrant cellular industry.

In well-established industries as oil & gas, car manufacturing, retail, and construction, it's a margin game. Revenues are varying over time; profits can only be improved by reducing costs and therefore improving the profit margin on revenue. The cellular industry is also a "margin game" in mature markets, but for different reasons. It is characterized by:

- **High Competition:** Intense competition among providers in mature markets erodes margins as services become commoditized.
- **High Capital Expenditure (CapEx):** The industry requires continuous, massive investment in infrastructure (e.g., 5G and soon 6G networks) and technology upgrades, which impacts net profit margins.
- **Focus on Volume/Subscribers:** Historically, the business model focused on expanding the subscriber base; now the challenge is maintaining margins through diversification into new services (like gaming or data analytics) as core services face commoditization.

The cellular network operators have a difficult stance. They must continue investing to deliver services at the forefront of technological development, yet they have increasingly become a commodity infrastructure, often taken for granted like rail or road network. Due to the latter, leadership is torn between having to adhere with business school rules of a margin business but at the same time having to be at the forefront of understanding the new generations of technology coming, influencing them to their benefit, and planning for the future.

**For us, as technologists, we therefore must understand this and deliver technology in a classical way of a margin business: increasing the top-line and bottom line of a profit-and-loss (P&L) statement. We must develop technology that addresses the P&L!**

## Pragmatic Bottom-Line Opportunity: Energy Efficiency, e.g. via Gearbox PHY

The bottom line can be improved by reducing the CapEx and hence the depreciation. As cellular technology evolves, this, however, would be equivalent to reducing the investment into the future. This is dangerous. On the other hand, an operational expenditure (OpEx) which does not add value is the line item due to energy consumption.

We have experienced a phenomenal improvement in terms of energy consumption per transmitted bit of the modem from 1G to 4G. The 1G analog modulation's induced power consumption was so high that initially the "handset" was conceived to be a car phone, less a portable device. The single-carrier modulation of 2G made it possible for exploiting the advancements of microelectronics via DSP (digital signal processing), however requiring a maximum-likelihood sequence estimator equalizer whose complexity grows exponential with the delay-spread of the channel, The code division multiple access (CDMA) spread-spectrum of 3G required for a RAKE receiver, whose complexity grows linearly with the number of channel paths taken into account. This grows linear with the delay spread of the channel. Finally, with 4G the OFDM modulation (orthogonal frequency division multiple access) was introduced into cellular. Its complexity is dominated by the FFT, whose size is chosen to grow linearly with the delay spread, however, whose complexity per processed sample grows only logarithmically with the FFT size. Hence, the equalizer of OFDM grows logarithmically with the delay spread.

This trend in equalization has been a factor in successfully driving data rates ever higher, without a major impact in power consumption of the DSP. As the bandwidth increased over time to support the increasing data rates, the effective delay spread increased as well, but not the DSP complexity due to innovations in modulation methods and accompanying required equalization techniques.

However, with 5G we have come to an end of new ideas, as we again are using OFDM. To support higher data rates the cardinality of the modulation was increased as well as the number of antennas supported in the MIMO transmission (multiple input multiple output). In consequence, microelectronic advances were not able to cover for this and as a consequence 5G networks have an increased power consumption compared to 4G.

A proposed solution named Gearbox PHY [4,5] is to capture the fact that networks are seldom fully loaded. On 24/7 average, the traffic is far below maximum capacity in every cell. Therefore, it makes sense to standardize multiple modulation techniques and implement their respective modems side-by-side as separate "gears", using extremely energy efficient modulation techniques on average and only switching to the high data-rate modem "gear" which has high energy consumption only during the short periods where peak traffic is needed.

**Reducing the energy consumption and therefore improving the bottom-line of operators by 10x is a challenge. The Gearbox PHY seems to provide a viable solution.**

## Pragmatic Top-Line Opportunity: Coverage

Coverage remains to be a challenge, even 40 years into cellular network deployments. And, many people in the world live in rural areas without internet access today: ITU's current number is nearly 3 billion people still unconnected [6]!

To realize the ever-increasing demand in traffic, the data rate of the physical layer has been boosted via increasing the QAM cardinality and number of MIMO streams has, however, at the cost of lowering the receiver sensitivity and the link budget. This is one reason why the inter-site distance has been reduced, making it more and more difficult to cover rural areas without massive densification, which poses a financial challenge. Why shall one invest into an expensive infrastructure that has very low utilization?

In the days of 2G modulations with nearly constant-envelope were chosen to minimize the RF transceiver power. We experienced very good link budget and could operate with very good receiver sensitivity. This allows for GSM extended-range cells to cover 200 km radius, a reason why we remain having GSM in wide areas of South America and Africa today. However, the modem DSP per bit is complex due to the MLSE equalizer. In the meantime, we know that frequency-domain equalization [7] can also be applied if the signal packet were designed accordingly. Again, making the DSP a logarithmic effort in terms of channel delay spread. Impulse radio is even more energy efficient and the receiver sensitivity is even higher.

Therefore, to address the coverage challenge one could again use a Gearbox PHY approach. Urban and suburban cells would have all gears, supporting extremely high data rates as traffic demand dominates the base station deployment. In rural areas base stations could be installed that only have the lower gears, supporting e.g. only up to 50Mb/s. These could be way more energy efficient, provide extreme coverage, and would be far less costly compared to a base station built to deliver rates in the multi-Gb/s range.

An alternative clearly is the use of non-terrestrial networks (NTN), in particular satellite networks. Due to the drop in satellite launch cost per kg weight, this can provide another viable solution. However, covering the nearly 3B nonconnected people will most likely not be possible with an ARPU (average revenue per user) far below $5/month, as required in many unconnected areas of the earth. A coverage-providing Gearbox PHY could be the more cost optimal solution, or as an intermediate step between an NTN and a full terrestrial rollout.

**Connecting the unconnected and providing global seamless coverage is a goal. With the Gearbox PHY umbrella-cells a range of coverage radius of approximately 100 km becomes a viable way forward in achieving this.**

## Top-Line Opportunity: Consumer Robotics

5G introduced URLLC to support remote control of robotic devices. We have observed many use cases for industrial and business applications. Visible examples are cleaning robots in public spaces, 5G drones, logistics robots, agriculture robotics. All are professional business use cases, and all with cellular connectivity. The vacuum cleaner robots at home is reconnected with WiFi so far. We are at the verge of robotic helpers and companions at a large scale. Examples are:

1. Home cleaning
2. Kitchen helpers
3. White good robots doing the wash
4. Mobility (autonomous cars)
5. Local mobility (wheel chairs, exoskeletons)
6. Entertainment/Gaming
7. Gardening
8. Sports
9. Companions, e.g. robotic pets
10. Tools

Assume you bought one personal mobile robot (PMR) of every of the ten categories every 10 years. This would result in buying on average one PMR per year. The cell phone renewal rate is currently around one every 3 years. This would mean:

**The PMR market is at least 3x larger than the mobile phone market**

This is substantial, and provides a nice opportunity for cellular networks. And this does not account for drones and other professional logistics applications. They come on top!

And the opportunity becomes even larger when taking the following into account. Today's Waymo or Zoox autonomous cars are equipped with a very large number of sensors to enable driverless level-5 [8] performance. The cost markup over a car driven by humans is large, more than double. Assume the network was providing the missing sensing for a car equipped and capable of level-3 driving to achieve level-5. Then this would be way more cost effective. Take the following back-of-the-envelope calculation:

> *If the markup from level-3 to level-5 were $50k and the car was driven 250K km within its life time, this results in 20 cents per km additional costs, not taking interest into account. If the network provided the necessary sensing for 10c/km this would half the price!*
>
> *Now remember the many use cases for PMRs listed in the previous section. Assuming this pricing of 10c/km and 2000 km of PMR service provisioning per month. This would amount to $200/month additional ARPU.*

**PMRs and professional robots are a great top-line opportunity for network operators. Their development will not happen overnight, but the prospects are great.**

## Pragmatic Top-Line Opportunity: Integrated Sensing & Communications at FR2

The above-mentioned service requires to install new infrastructure, e.g. LIDAR and RADAR at street crossings, and/or new integrated sensing within the licensed communications bands. A pragmatic approach could be to use the existing FR2 for sensing (cellular frequency range 2, typically between 24.25GHz and 30GHz. This band has not been heavily used for communication services, but is ideally suited for RADAR [9]. Installing RADAR at this band gives operators the chance to capture the static environment as well as the moving targets.

The most pragmatic way to implement this is to use an already standardized protocol. In case FR2 is used for communications the UE operates in dual connectivity with an FR1-anchored master cell group (MCG) handling control signaling and call management, while FR2 cells are used as a secondary cell group for high-rate user-plane transmission. Equivalently, FR2 radar can be scheduled and mastered and scheduled by an MCG at FR1, only using FR2 for sensing [9].

A mono-static, bi-static, or multi-static RADAR could enable positioning as well as RADAR imaging. For professional services, e.g. logistics delivery on ground or by drone, this capability is needed as well. Not only PMR but all professional applications require sensing.

Importantly, note that sensing data can be very personal and therefore privacy is a very important aspect to be taken into account. Operators are highly regulated concerning privacy of phone calls and Internet access. They are a natural for being the host of sensing data.

**Integrated sensing and communications done right gives the operators the chance to monetize their most valuable asset, the sensing data. The future of operators is not only to deliver connectivity, but to provide access to data. At the age of AI this clearly is another interesting revenue opportunity.**

## Important Top-Line Differentiator: Trustworthiness

In the coming new world of robotics and XR, commencing with 6G but clearly developing over the next decades, privacy will become a major concern. However, not only privacy is a characteristic of concern. When encountering PMRs and professional robots we must trust them at least as much as trusting people. It therefore is important to understand an overarching concept of trust and trustworthiness, as it has been developed in social sciences over the last half century, see in particular [10, 11].

The 5G and O-RAN standards were therefore analyzed in the study [12] concerning five characteristics:

1. Confidentiality
2. Integrity
3. Availability
4. Accountability
5. Privacy

An even more comprehensive list of objectively measurable characteristics to be analyzed in the future has been standardized in the meantime as [13] shows that current standards default dramatically. How can we make subjective decisions based on the situation encountering a robot when the network fails to be trustworthy?

The paper [14] conceptualizes trust and trustworthiness in communications as a first step. This is just a start. We must get going and develop finer models to tackle the world of robotics age ahead.

**Trustworthiness and trust are key for human-human interaction. 6G must embrace this as this is the basis for monetizing most top-line opportunities ahead. And this starts at the basis, building the right chip architectures [15], see also [16].**

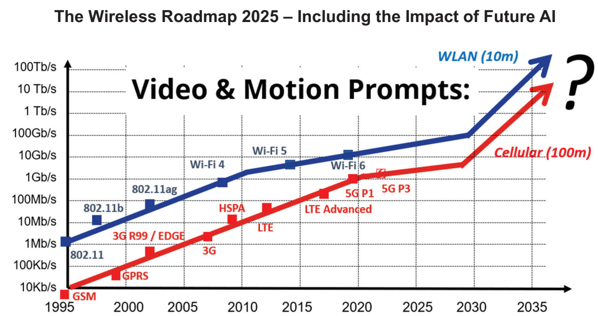
## Top-Line Opportunity: AI induced Traffic Growth

Formerly we were used to cellular data traffic to grow exponentially. Therefore, the radio access network also followed this trend to provide the bandwidth required to serve the appetite for data. It nearly followed Moore's law, doubling every 18 months which is the same as growing by 10-fold every 5 years.

Cellular traffic growth has been nearly flat in the last 4 years. It shows merely a 20% growth and the growth is continuing to be falling. When analyzing the published traffic growth in [17], it shows an exponential decay. This is due to the fact that in absolute numbers traffic has stopped growing exponentially by the end of 2021. Important to note: November 2021 was when LLM AI (large language model) hit the market. It might be that people were busy with interacting with AI and less with data-heavy video content.

Therefore, let us learn from the past and project the future: Cellular data usage exploded with 4G. It was less the cellular technology but video content being downloaded and uploaded while visiting social media sites that created this demand. In 2G data was dominated by SMS, text messaging. In 3G it was mainly email and attached files that created the demand for data. At the end of 3G and then with 4G, social media video clips hit the users by storm. We saw an explosion in data usage. Now where do we stand in AI prompting? At first, we were able to prompt simple text messages. Now we can upload files and in return receive files. Wide-scale video prompting is only expected to be ready for broad use in 2027. Then we will be able to upload reels and whole videos, or capture the input by camera, and in return receive fantastic animated video content.

And then come the PMRs. As we interact with them, AI is at work. Cameras and RADAR will capture the environment and our gestures. This will be uploaded to AI computing systems and in return the PMR needs to react, swiftly! This means the days when we are used to waiting 10s of seconds and minutes for the reply to a prompt will be over. Today we can average-put data transmission as real-time plays hardly any role. Tomorrow, when interacting with robots, peak data rates and latency matter. Will this wave influence the wireless roadmap of [18] and refreshed in [3]? And will it look as sketched in the update below?




**It is sensible to assume that we are at the verge of a large wave of increase in data traffic in cellular networks! We must get ready and have energy optimizations ready, as e.g. the Gearbox PHY. The days of slow growth will most likely be over soon 6G will be turned on when this wave hits the market. Only planning for low-growth is planning for failure?**

## Synthesis

The cellular industry is at the verge of an exciting new wave. Let us focus on the top-line and bottom-line opportunities ahead. Personal mobile robots and motion capture AI prompting are just two applications to mention that seem natural to project. They both create valuable growth opportunities for the industry and must be addressed by 6G. They require the development of many solutions to overcome technical challenges. A pragmatic approach seems most promising.

Operators have a new chance for revenue ahead. As robots require sensing, it seems more sensible to implement a vast amount of the sensing within the network and implement only basic sensing in robots, not overloading every robot with costly large sensing. At a meta-level this is equivalent to having compute power in terminals, but for many applications relying on data centers to provide additional performance. Making the network a source for sensing and its data makes this another exciting opportunity for networks of the future.

But we must not forget that trustworthiness and trust must be addressed at a very deeper level as done up to now in 1G-5G cellular standards. For the implementation we need trustworthy platform chips as an anchor for enabling this future [15].

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## Acknowledgement


The vision presented in this paper would not have been possible without the daily interactions with my teams at TU Dresden and at the Barkhausen Institute. And, I thank my colleagues of the scientific community for all the discussions. The work is supported by Vodafone, the governments of Saxony, Germany, the European Commission, many industrial partners as well as the European Research Council and the German Science Foundation (Deutsche Forschungs-Gemeinschaft: DFG).Many parts of the vision have been presented at keynote talks at IEEE conferences.


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Gerhard P. Fettweis, earned a Ph.D. under H. Meyr at RWTH Aachen (Germany) in 1990. After a postdoc at IBM Research, San Jose, he joined TCSI, Berkeley, USA. Since 1994 he is Vodafone Chair Professor at TU Dresden, Germany. Since 2018 he is also founding Scientific Director & CEO of the Barkhausen Institute. He researches wireless communications and chip design, coordinates 5G++Lab Germany and the German Cluster-for-Future SEMECO. His team spun-out 28 tech startups, and he initiated 6 platform entities. Gerhard is member of the US National Academy of Engineering, the German Academy of Sciences (Leopoldina), the German Academy of Engineering (Acatech), and Fellow of IEEE, VDE/ITG, National Academy of Inventors, EURASIP, WWRF, and DATE. He is active in organizing IEEE conferences.