EURASIP Position Paper on Signal Processing Challenges for Communications beyond 5G

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Abstract

This position paper collects topics indicated by the members of the EURASIP SAT SPC group as promising and challenging research directions over the next 3-5 years time-horizon, beyond what can be considered as “mainstream” 5G. In fact, it is recognized that the 5G research in the framework of EU-funded activities has been polarized and framed into the various 5GPPPs, which have a strong applied R&D flavor and are clearly aimed to define the convergence towards a first round standardization, in order to meet the targeted timeline of 5G. At the same time, EURASIP SAT SPC would like to attract attention on more open-ended, academic-oriented, challenging, and fundamental research topics, more properly adapted to a thriving scientific community that represents a major strength and a main asset for the sake of EU leadership in Information Technology.

I. Research Topics and Challenges

For each of the topics listed in this section, we have strived to point out: 1) Relevance (why is this important?); 2) Is the topic “beyond 5G”?; 3) What are the novelty and the main challenges?.

A. Processing of side-information for improving network performance

- **Relevance (why it is important?):** The acquisition and evolution of channel state information (CSI) is important for network throughput and dependable communications. CSI estimation and prediction in transceivers is heavily based on linear estimators and largely ignores side-information. Side-information about the propagation environment, traffic patterns, user mobility (to name a few) is rarely exploited today, but promises large benefits.

- **Does it fulfill the requirement of "beyond 5G"?** From early preview on candidate 5G technologies (e.g., massive MIMO and mmWaves with hybrid beamforming) it seems that the rationale for the air interface design remains the classical per-frame pilot-based approach, where CSI is estimated on a frame by frame basis from pilots and time division duplex (TDD) reciprocity or pilots and closed-loop feedback.
- **Novelty and theoretical challenges**: Sensor networks employ communications to aid in data acquistion and inference. This is a well established research topic. Vice versa: Side-information from sensors may help in harsh communication environments. This aspect is novel. Significant side-information is expected to be available in the internet-of-things, enabled by the ubiquitous availability of geographical information services and through the fusion of sensor data (e.g. device location and orientation, device speed, environmental map, device cooperation, to name a few options). The interest in propagation-aware channel state predictors is on the rise because the number of degrees of freedom for the channel state increases strongly with the advent of wideband, high-mobility, and cooperative transceiver technologies. Exploiting side-information may help in limiting this curse of dimensionality. Theoretical challenges: Which side-information is most useful for high throughput? Which side-information is most useful for dependable communications? How can side-information from unreliable sources be exploited? How can side-information be gathered and shared?

B. Satellite networks as part of beyond 5G

- **Relevance (why it is important?):** 5G does not really address the needs for mobile data and connectivity of those 3 billion people who live beyond the reach of mobile networks in rural, suburban and remote sites. In short, it seems that 5G will give people who already have the most even more. In contrast, cost effective solutions for ubiquitous communications need to go beyond the 5G mainstream. New technologies are radically bringing down costs for satellites, including new launchers, assembly line satellites, on-board processing, and so on. These technology advances in satellite technology need to be matched by a corresponding dramatic development of signal processing and communication capabilities, as well as by a holistic and systematic understanding of hybrid terrestrial/satellite communication network design. As space funding is limited, the main strategy has been to monitor the technological developments for ground applications, and at the right time to provide the required funds to tailor these technologies to meet the needs of space applications. If communication capabilities are to be increased worldwide, it is time to change this strategy.
- **Does it fulfill the requirement of "beyond 5G"?** 5G will not provide ubiquitous communications. In contrast, satellite networks provide coverage, disaster resilience, capacity, that terrestrial wireless networks cannot provide and therefore, both networks are complementary. The topic is only shyly included for consideration by the EU in the next Work Programme 2016-17.
- **Novelty and theoretical challenges**:

1) New network architectures and constellations, LEO, MEO. High Altitude Platforms and Low/Medium Earth Orbit constellations promise lower communication delays and better integration with aerial and terrestrial networks, but pose new problems into the required signal processing for communications. Channel models for the user and the feeder beams are lacking and the channel impairments due to Doppler shift and Doppler rate are much more important than in Geostationary Satellites, where they are almost inexistent. Among other: fast synchronization algorithms are required to avoid the interruption of the Service, advanced multicarrier waveforms that are robust the time-varying nature of the channel should be investigated.
2) Aeronautical and Professional Link Designs for Satellite Systems at Extremely High Frequency Bands. New satellite links can employ extremely high frequency (EHF) bands and particularly Q/V band (40/50 GHz) and W band (70/80 GHz). For example, two types of scenarios can be addressed: i) Aeronautical systems operating at EHF bands (AERO) to provide broadband Internet services to the cabin of commercial airliners; ii) Systems accommodating feeder or mesh professional links at EHF bands (MESH) to provide ultra-high data rates involving professional users with medium to large ground stations. Channel models are lacking in these frequencies.
3) Seamless services over hybrid terrestrial-satellite networks. From the signal processing point of view, further research on resource allocation and management techniques are needed such that non-uniform cooperative resource allocation strategies are developed considering various parameters specific to each cell, segment and access/backhauling technology. In order to lower deployment costs, satellite systems aim at full frequency reuse among their users, and between terrestrial links. This fact changes the paradigm from a noise limited to an interference limited one, which pushes for designing new interference resilient codes, interference constructive modulations and joint scheduling and precoding or detection schemes, among others.
4) Optical free-space communications. There is a need of optical communications inside the Satellite because the intra-satellite communication requirements can reach several Tbps. Also because of the EMI, low mass, low volume and mechanical flexibility characteristics of fibers that are important in a Spacecraft, linking equipment with equipment, board to board and chip to chip with: digital processing, analog processing and photonic processing of microwave signals is needed.

   There is also a need for free-space laser links between satellites because the higher directivity of the optical beam allows higher data/power efficiency (more Mbps for each Watt of power), which is critical to power-limited systems. However it has higher Pointing Acquisition and Tracking requirements.
5) On-board signal processing. Actual GEO (geosynchronous satellites) Telecom Satellite can vary from being a classical Analog Repeater (?transponder?) to a full Digital Exchange Centre. However, in order to further increase the downlink bandwidth on-board signal processing is desired. As modern GEO satellites are

required to remain functional for up to 20 years after launch, for on-board processing deployment, FPGAs must be able to survive the radiation environment for the duration of the satellite life without any destructive or catastrophic failures, such as single-event latch-up or configuration upsets. Actual radiation-tolerant FPGAs solve the signal processing bottleneck. Modern satellite Payloads carrying Digital Processors require optical communications to handle several Tbps with minimum power consumption. Free Space Optical communications establish the means to generalize the use of Photonics by achieving the signal processing functionalities and hence creating entire Photonic systems such as Photonic Payloads (including electro-photonic ADCs and BFNs) and fully Photonic communication (and Sensing) .

C. Quantum-Assisted Design of Wireless Systems

- **Relevance (why it is important?):** The potentially excessive complexity of numerous optimal classic communication schemes, such as the Maximum Likelihood (ML) Multi-User Detector (MUD) prevents their practical implementations. The design challenge becomes even more grave, when we consider the ML-detection problems of multi-user, multi-cell network-MIMOs operating in practical dispersive scenarios. In this context the powerful parallel processing capability of Quantum Search Algorithms (QSA) can be beneficially exploited for solving large-scale wireless optimization problems. Many of these classic problems can be more efficiently solved with the aid of QSAs, but this requires substantial further research from the broader community. This is particularly the case, when solving challenging multi-component optimization problems by finding the Pareto-front for jointly optimizing numerous parameters, such as the BER, transmit power, delay, etc under time-invariant channel conditions.
- **Does it fulfill the requirement of "beyond 5G"?** This topic is highly exploratory and definitely goes beyond the boundaries of 5G mainstream R&D.
- **Novelty and theoretical challenges**:
  1) This research is in its infancy owing to several factors, amongst others due to the extremely short coherence-time of the available quantum circuits, which hence impose both quantum bit-flips as well as phase flips. A potential remedy to this problem is to use the family of quantum-codes, synonymously also referred to as stabilizer codes.
  2) Promising opportunities open up by communications over quantum channels, such as their increased capacity potential. Classically the mutual information between the channel's input and output has to be maximized. Naturally, in case of quantum channels the capacity has to be redefined, leading to diverse scenarios to be considered.
  3) A natural distinction concerning the channel capacity definition is, whether we restrict ourselves to classic bits as the system's inputs/outputs or not. In case of classic inputs/outputs we encode the input symbols/states

into quantum states, send them over the channel and carry out a decision at the receiver side, effectively constructing a 'classic-quantum- classic' processing chain. This is a natural approach, since humans can only process classic information. By contrast, if we do not restrict ourselves to classic inputs/outputs, we are capable of dealing with quantum channels within larger quantum systems.

4) The most important question arising in this context is, whether quantum channels are capable at all of increasing the achievable capacity and if so, under what conditions. The answer is definitively yes. Moreover, as a stunning result, redundancy-free error correction is possible over noisy transmission media, at least for a specific subset of quantum channels.
5) And the science-fiction saga still continues... one of the hot research topics in this field is referred to as super-activation of quantum channels. Naturally, there are numerous quantum channels, which have zero capacity in the context of classic information transmission. But stunningly, when considering two of these zero-capacity channels used in a parallel manner and, additionally applying a special decoder operating by obeying the quantum-domain rules, the output of the decoder starts to deliver information...
6) EXtrinsic Information Transfer (EXIT) charts have to be redefined for quantum systems and used for designing radically new systems. Since the so-called 'observation' of the quantum states destroys their fragile quantum-state, this 'observation' can only be carried out after all computations have been concluded in the quantum-domain. This requires the employment of syndrome-based quantum-codes, which is capable of avoiding the observation of the qbits.

D. Network-Assisted Self-Driving Objects

- **Relevance (why it is important?):** Self-driving cars, and self-driving/coordinated flocks of drones are attracting more and more attention, moving from curious TED-style technological toys, to tools of practical use with a potentially revolutionary impact on everyday's life. Nevertheless, the current approach consists of putting both the sensing and the main intelligence of the control system into the vehicle itself, somehow forgetting the fact that the vehicle is connected to a wireless network with infinitely more powerful "cloud" computing capacity. We borrow an example from the recent revival of speech recognition systems such as SIRI and Google Assistant: speech recognition has been around for 20 years, and was based on the traditional HMM approach and Welch-Baum algorithm. This never took off, and the performance of "conventional" automatic multiple-choice menu machines have been ridiculously disappointing, to the point that many commercial call centers reverted to human to human interaction. Nevertheless, SIRI and the new generation of voice recognition systems have immediately encountered an enormous success. This is why the recognition function is not implemented in the phone (limited computational capacity and storage), but it is implemented in the cloud, leveraging the enormous power of Big-Data, i.e., with the help of positioning, maps, user personal profile and history of previous searchers, and so on.

The phone simply samples and compresses the speech signal, sends it to the cloud via wireless, receives the answers and presents them on the web browser interface.

Now, we envisage cyber-physical cloud-based systems where a large number of coordinating and moving objects (cars, drones) are jointly controlled via wireless networks. The communication problem here consists (in analogy with SIRI), of conveying the sensing information (typically the result of some analog source, such as a video camera, inertial navigation parameters, GPS if available, radio localization measurements) to a cloud computer which executes the (joint) controller, and conveying back the control commands from the controller to the vehicles. The standard separated "layering" approach (source, compression, TCP/IP, MAC/PHY) yields intolerable delay and sensitivity to post-decoding errors (resulting in dropped packets, NACKs, retransmissions, and so on). For such system, we advocate a low latency and low complexity joint source-channel coding approach, where the sensing source data streams are directly mapped over the channel symbols (e.g., using unquantized QAM and OFDM) through a randomized rank-reducing linear compression map (e.g., exploiting the rich theory of compressed sensing).

- **Does it fulfill the requirement of "beyond 5G"?** Joint source-channel coding has been widely studied from a theoretical viewpoint, but in practice has generated only "rate adaptation" schemes, compliant with the current layered protocol stack. Furthermore, the so-called "tactile internet" line of work has tackled mainly the problems related to the design of "new waveforms" with low precoding latency (e.g., moving from cyclic prefixed OFDM to some kind of Gaussian-shaped filterbank multicarrier scheme). We believe that in order to tackle the problem of distributed sensing and control over wireless networks a more fundamental and holistic approach must be taken. It is a simple matter to verify that the latency and delay jitter introduced by a layered protocol stack, even in the presence of 'new waveforms" at the physical layer, will not be able to meet the constraints of distributed control of large cyberphysical systems over wireless networks. The advocated joint source-channel coding (direct mapping of source symbols over channel symbols) is clearly against the current data-oriented layered architecture based on the traditional APP/TCP/IP/MAC/PHY protocol stack approach, which is still at the center of 5G. Therefore, the research direction proposed here represents a radical departure from this paradigm, and targets specific novel tasks of future wireless networks beyond the mainstream 5G, including the "tactile internet" buzzword.
- **Novelty and theoretical challenges:**
  1) Joint-source channel coding & compressed sensing: leveraging the fact that linear maps are well conditioned with respect to noise (graceful degradation, no packet losses or retransmissions).
  2) Efficient design of plant state estimators/trackers from compressed sensor signals. In particular, in combination with computer vision and feature extraction from video.
  3) Investigation of the feasibility region of the joint control and communication problem: we need to study the

intersection between the region of sampling rate, distortion and delay achievable by the network, and the "demand" set of the controller. If such intersection is not empty, the control and communication problem is feasible. Otherwise, the controller has to step back, possibly put some vehicle in "hold" mode, and ask for less.

4) Extension of the same ideas to similar systems, e.g., very large number of home batteries, coordinated via wireless in order to guarantee frequency stability of the power grid in the presence of renewable sources, industrial robots in a wireless-controlled plant, and so on.
5) The research here is highly interdisciplinary, requiring synergy between communication and information theory, wireless networks, resource allocation and real-time scheduling, control theory, computer vision, Big-Data and Machine Learning.

E. Inferential Networks

- **Relevance (why it is important?):** Beyond 5G networks can definitely extend the typical role of wireless networks devoted to secure and efficient communication. In particular, we foresee that they can serve as inferential networks to infer various types of processes (in addition to transmitted messages for multiuser communication) in a multidimensional space. Spatiotemporal signal reconstruction of stochastic processes from samples randomly gathered in a multidimensional space is a crucial problem for a variety of emerging applications (e.g., environmental monitoring, crowd tracking, dynamic objects control). In such perspective, the diffusion of new generation phones with additional sensing capabilities and the extremely-high elaboration capability expected for beyond 5G network infrastructure are a key of success for random sampling in $\mathbb{R}^4$. Multidimensional signal reconstruction has to face with uncertainties in the observations (measurements and sensors positions), signal properties (signal spectrum and spatial correlation), and sampling properties (inhomogeneous sample spatial distribution and sample availability). The signals emitted by beyond 5G network units can serve as signals of opportunity for inferring positions of objects in the space and for controlling their movements without the need of dedicated infrastructures and with reduction of electromagnetic pollution.
- **Does it fulfill the requirement of "beyond 5G"?** This topic is definitely beyond the boundaries of 5G mainstream R&D.
- **Novelty and theoretical challenges:** Multidimensional random sampling generalizes the reconstruction of a stationary random process in one dimension, which, for regular sampling, was addressed by Balakrishnan and Lloyd based on Kotelnikov and Shannon sampling theory, while, for irregular sampling, was described by a Levinsons theorem establishing the condition for perfect reconstruction. Many authors have worked on this since the end of eighteens century (mainly in one-dimension), but none of them have studied multidimensional random sampling and optimal interpolation in multiple dimension when nodes are randomly scattered in space

according to an inhomogeneous spatial distribution and the observations are affected by noise and by imperfect knowledge of sample positions. The inference of sensors positions using signal of opportunities presents several open problems, especially in soft-decision localization algorithm design and clutter removal filtering.

F. Hybrid VLC and Radio Networks

- **Relevance (why it is important?):** Increased spectrum-utilization will firstly rely on dynamic radio-spectrum access in unused licensed or unlicensed bands or geographically-dependent unused bands (e.g. TV White Spaces). Secondly, and arguably more importantly, the migration to millimeter-wave frequencies should allow for efficient exploitation of massive amounts of available spectrum. Although bandwidth is plentiful in millimeter-wave bands, communication is restricted to small areas and mainly line-of-sight links especially due to power-limitations in mobile terminals. This requires a densification of the radio network which will be seen in the form of an explosion in the deployment of small-cells with an efficient, high-throughput and low-latency optical backhaul. In addition to such millimeter-wave small-cells, the use of free-space optical channels has been proposed for high-bandwidth wireless data communications, especially in the form of visible-light communications (VLC). VLC approaches using conventional LED lighting equipment that can be bought in hardware stores used in conjunction with relatively low-cost and tiny photo-sensors have been shown to be feasible for transporting high-bandwidth spectrally-efficient OFDM waveforms [reference], currently up to 1.6 Gbit/s with a single-color LED. One of the interesting consequences of using VLC is that the deployment of communications infrastructure is coupled with lighting, and, moreover, good lighting coverage will ensure good communication links. This could even be true in the case of non-line-of-sight scenarios since modern indoor environments are conceived with materials that guarantee good lighting conditions even with reflections. Exploitation of this symbiosis will be extremely beneficial in locations such as airports, shopping centers, office buildings, super-markets, etc., which are all examples of locations where high-throughput wireless communications are expected with even todays smartphones. Another clear benefit of the symbiosis is energy consumption, in the sense that the communications component does not require additional power for transmission since it exploits the high-power transmission used for lighting.

  Similarly to radio-based systems, multi-port transmission (i.e. MIMO and/or adaptive beamforming) is feasible with LED lamps, which are usually an aggregation of many low-power emitters. Innovative multiport processing for LED-based transmission is still in its infancy. In particular, the benefits of MIMO transmission, whether point-to-point or multiuser-MIMO, are yet to be determined. This is primarily due to insufficient understanding of the propagation characteristics of free-space optical links. Coordinated multipoint transmission (CoMP) may be simpler with VLC transmitters because of the number of lighting sources that are available in typical indoor environments. Finally, through CoMP, VLC transmission could provide very accurate positioning possibilities.

This is due to the fact that multiple optical channels with significant carrier-spacing (orders of GHz) can be used to allow terminals to position themselves with extremely high accuracy.

Industry cooperates to promote the use of VLC through the so-called LiFi or light fidelity consortium. LiFi approaches the standardization of VLC waveforms and protocols through the now out-of-date IEEE 802.15.7 standard proposal. The pitfalls in this approach are firstly that the physical-layer waveform does not consider and is not particularly well-adapted to high-spectrally efficiency techniques (OFDM, MIMO, beam-forming etc.) and secondly that the proposed protocols are not conceived for tight (low-layer) heterogeneity with radio-systems. These are both extremely unfortunate with respect to the massive future usage of VLC technology. In the context of low-power terminals, like smartphones, VLC can make maximal impact if used for high-throughput downlink communications, either in the form of multicast/broadcast radio bearers or unicast bearers whose uplink counterpart (including necessary low-layer signaling for channel state information and channel decoding integrity) is transported using legacy radio services. It could be argued that a tight interaction between radio and optical components should be considered at the level of baseband processing as well. Since OFDM transmission is feasible on a free-space optical link, it is definitely worth considering using the same basic waveform and protocol stack for radio and VLC components. This would allow for a common baseband processing platform in both the small-cell transmitters and terminal receivers. Moreover, current access-layer protocols are perfectly adapted to the use of Downlink-only component carriers. The 40 MHz of so-called Supplemental Downlink Channels (1452-1492 MHz) will be used widely in Europe in conjunction with bi-directional carriers in the coming years. Adding VLC-based downlink channels could prove to be a cheap solution for boosting downlink bandwidth.

- **Does it fulfill the requirement of "beyond 5G"?** Yes. Current proposals in most of the worlds for the 5G patchwork are ignoring VLC. If the waveforms and signal processing components in terminals can be mutualized for radio and VLC, this could make it an interesting technology.
- **Novelty and theoretical challenges:**
  1) Co-located Multi-port transmission achieving firstly point-to-point and more importantly multiuser spatial-multiplexing with a single LED array. Secondly, the potential for highly-selective adaptive beamforming techniques using feedback on the radio-link. This will require extensive propagation measurement campaigns for the VLC component.
  2) Distributed Multi-port transmission using multiple spatially distributed LED arrays. This will also require propagation measurement campaigns for the VLC component and can show the potential benefits in terms of spatial-multiplexing and localization.
  3) Proper statistical modeling of the free-space optical channel for assessment of fundamental communication

limits.

4) The use of common baseband signal processing units for VLC and radio transceivers.
5) The capacity of the free-space optical link (even in the single-user case) is still unknown, although some high-SNR bounds have been found.

G. Networked Signal Processing and Wireless Fronthaul/Backhaul

- **Relevance (why it is important?):** The evolution towards 5G radio networks will include a paradigm shift in signal processing, namely the use of distributed and dynamic processing of radio signals in different parts of the network. In the simplest scenario, processing will be shared between so-called remote radio-heads (RRH) and centralized data centers which perform joint processing of the information coming from many RRH. The interconnection of the RRH with the data centers will typically be with a high-performance synchronous network or, because of deployment costs, via a mmWave wireless fronthaul network. In today's 4G networks this interconnection is from the RRH driving multiple sectors on the top of the antenna mast to a baseband unit (BBU) in a control room at the bottom of the mast. The RRH contain the radio transceivers and data converters and some limited amount of local signal processing. Currently the signal processing is limited to filtering and decimation/interpolation. In 5G the data centers will pool BBUs implemented on more generic computing equipment (Intel/ARM). The RRH will remain similar to today's equipment although perhaps starting to perform slightly more processing that can be done locally (e.g. DFTs for OFDM modulation/demodulation). In future networks, we foresee that the processing split between RRH and data-center will be dynamic depending on traffic load of the network, power consumption of the network, synchronization accuracy between RRH, processing capabilities of the RRH, and quality of the wireless fronthaul links. Moreover, we foresee the requirement for a very dense deployment of such processing-capable RRH with many different types of network interconnections with the data centers and mutual synchronization granularities. Note that this is in stark contrast with the notion of small-cells, where an entire basestation MODEM and protocol stack is hard-coded in the processing elements of the small-cell device and little or no signal-level collaboration with other small-cell devices is feasible. This evolved RRH architecture is a truly distributed processing environment and will call for new computer science skill-sets for the radio system designers. When these transport architectures are coupled with the growing number of sensor-based applications, the processing elements could also used dynamically for distributed data fusion at the application level.
- **Does it fulfill the requirement of "beyond 5G"?** The research advocated here represents a paradigm shift in distributed radio computing which goes beyond any particular radio transmission standard. 5G and even 4G networks could actually be built using such a signal-processing architecture. To efficiently realize some of the techniques proposed by the research community (e.g. distributed MU-MIMO) such an architecture could prove to

be necessary. Moreover, the radio standard (even 5G) could benefit from such architectures if they are conceived under the assumption that the network will be deployed with distributed processing under centralized control.

- **Novelty and theoretical challenges:**
  1) Massively distributed computing for radio signal processing. This is a complete paradigm shift and requires new skill-sets for the radio system designer.
  2) Potential for synergy/resource reuse with distributed application-layer signal processing (e.g. sensory data and multimedia)
  3) Network synchronization mechanisms and centralized timing/frequency resynchronization through signal-processing.
  4) Design of efficient and reliable wireless fronthaul at mmWaves, i.e., the technology behind the so-called "wireless fiber".

H. Open-source tools for radio network innovation

- **Relevance (why it is important?):** Open-source has made a very significant impact in the extremities of current wireless and fixed networks, namely in the terminals due to the Android ecosystem and in cloud infrastructure due, in part, to the OpenStack ecosystem (http://www.openstack.org/). The access network components, or more specifically the embedded systems comprising the radio modem signal processing and access-layer protocol implementations, can be seen as the final frontier for open-source implementations. This is mainly due to the revenues generated by intellectual property in this segment of cellular technology. Through innovation in open-source licensing, the OpenAirInterface (OAI) Software Alliance now provides a joint academic-industry ecosystem for the core (EPC) and access-network (EUTRAN) of 3GPP cellular systems with the possibility of interoperating with closed-source equipment in either portion of the network. In addition to the huge economic success of the open-source model, such an ecosystem can be a tremendous tool used by both industry and academia to jointly foster wireless innovation. More importantly it ensures a much-needed communication mechanism between the two in order to allow academia closer to have a direct impact on cellular technologies which are controlled today by major industrial players in the wireless industry. In the context of the evolutionary path towards 5G and beyond, there is clearly the need for open-source tools to ensure a common R&D and prototyping framework for rapid proof-of-concept designs. This will reduce the cost of radio network components since the great majority of the development will be collaborative and include university, research centers and a more general population of hackers as part of the workforce. This is also valuable training for engineers that will later join industries using similar or the same core implementation.
- **Does it fulfill the requirement of "beyond 5G"?** Yes. As exemplified by the 5GPPP set of projects, it is pretty clear that 5G is still driven by a small set of very large companies, with tendency to create monopoly of IP and

negotiate with each other on the basis of a patent pool, as members of a restricted club, clearly geared to exclude faster innovation coming from smaller and more dynamic “startup” companies. Unfortunately, this model in the long term is not competitive, and lead necessarily to either damping of the revenues or artificially high equipment costs. The Silicon Valley ecosystem has widely proven that innovation needs open-source to thrive (e.g., Linux, Android). Bringing open-source into this market segment, and to create the academic-industrial symbiosis is an effort that will require years of work. 4.5/5G will allow for experimentation making beyond-5G more likely for commercial impact.

- **Novelty and theoretical challenges:**
  1) Creation of a global open-source ecosystem between academia and industry through collaboration with standards-making bodies (e.g. ETSI, 3GPP, IEEE)
  2) Spreading of knowledge through distribution of and training with open-source tools. Making Europe (instead of Silicon Valley) the heart of this development
  3) Bringing the technologies into the classroom and more general university activities
  4) Developing of a software library of signal processing and upper layer protocol fundamental functions with controlled execution delay, such that they can be interconnected and run on general purpose machine (e.g., cloud computers) and provide predictable and reliable performance
  5) Large-scale collaboration with major industry