Cooperative Passive Coherent Location: A Promising Service for Future Mobile Radio Networks

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***Abstract*—5G promises many new vertical service areas beyond simple communication and data transfer. We propose CPCL (Cooperative Passive Coherent Location) being a distributed MIMO radar service which can be offered by mobile radio network operators as a service for public user groups. CPCL comes as an inherent part of the radio network and takes advantage of the most important key features proposed for 5G. It extends the well-known idea of passive radar (also known as Passive Coherent Location, PCL) by introducing cooperative principles. These range from cooperative, synchronous radio signaling, and MAC up to radar data fusion on sensor and scenario levels. By using both software defined radio and network paradigms, as well as real-time mobile edge computing facilities intended for 5G, CPCL promises to become a ubiquitous radar service which may be adaptive, reconfigurable, and perhaps cognitive. Because CPCL makes double use of radio resources (both, in terms of frequency bands and hardware), it can be considered a green technology. Although we introduce the CPCL idea from the viewpoint of vehicle-to-vehicle/infrastructure (V2X) communication, it can definitely also be applied for many other applications in industry, transport, logistics, and for safety and security applications.**

***Index Terms*—5G Verticals, Vehicle-to-X (V2X), Cooperative Driving, Intelligent Transport Systems (ITS), Joint Communication and Radar, Passive Coherent Location (PCL), Passive OFDM Radar, Distributed MIMO Radar Network, Radar Resource Management, High-Resolution Radar Parameter Estimation**

Introduction

The fifth generation (5G) mobile communication networks will be driven by several key enabling technologies [1]. Among these are software defined adaptivity and resource allocation on the radio and network layers, massive MIMO, new frequency bands and waveforms, device-to-device connectivity, etc. This, together with low latency communication and edge cloud computing, will open new horizons in service delivery. We will observe a transform of radio networks from pure wireless connectivity to a network for services, which will foster new fields, use cases, and business models for vertical industry applications.

Many of these, including automotive, industrial automation, and security tasks, will need location services. Whereas positioning of mobile devices and objects provided with wireless tags is already widely discussed, there is an increasing demand for positioning of objects that are not equipped with any specific technical means to deliver their location. Obviously, this task requires radar location principles, which rely on proper radio illumination of the objects of interest and sensing of the backscattered signals. Here, we propose the new principle of Cooperative Passive Coherent Location (CPCL), which is to be an integrated radar service of future mobile radio networks. Essentially, CPCL extends the well-known idea of passive radar (also known as Passive Coherent Location, PCL). Whereas PCL does not consider any cooperation between radar illuminators and sensors, we assume for CPCL that all radar nodes belong to the same network. This way, CPCL will turn the mobile radio networks into a distributed Multiple Input Multiple Output (MIMO) radar network, which opens a wide scope of cooperation between sensor nodes reaching from cooperative bi-/multi-static target scene illumination up to radar data networking and fusion. Synchronous signaling and Medium Access Control (MAC) schemes, at the same time, will solve many problems that conventional dense radar networks will be faced with in the future. The scalability and flexibility of 5G will allow tailoring of CPCL to a variety of application classes. Exploiting the real-time computing facilities of the Mobile Edge Cloud (MEC) will support radar data fusion on sensor and scenario levels and eventually enable the Mobile Network Operators (MNO) to offer CPCL as a service for public user groups. Within the 5G perspective, CPCL promises to become a ubiquitous hybrid communication and radar service, which may be adaptive, reconfigurable, and even cognitive. At the same time, CPCL takes advantage of the most important key features proposed for 5G. Although it seems to be applicable to many vertical services, we introduce the CPCL idea from the viewpoint of cooperative driving. Therefore, this article starts with a short and concise overview of vehicle-to-vehicle/infrastructure communications (V2X) with an emphasis on LTE V2X and the 5G perspective. We give a survey of the current situation of automotive radar as one location sensor principle for automated and cooperative driving and review conventional passive coherent location. Based on this, we elaborate on the basic idea of CPCL, highlight the challenges and the potential of CPCL as an inherent radar service in future 5G networks, and summarize the most important related research questions. We also give a first measured example to demonstrate its feasibility.

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Current Situation in V2X Communications and Radar Sensing

CPCL builds upon various technologies and developments in wireless mobile and vehicular communication networks, as well as traditional radar sensing approaches.

5G Perspective for V2X Communications

With the long-term evolution-vehicle (LTE-V) standard, 3GPP recently has made a big step forward towards 5G vehicle-to-everything (V2X) communications. This includes both Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communication. The development is now accelerating with the recently formed global cross-industry 5G Automotive Association 5GAA having decided to join 3GPP. This alliance proposes the coexistence of cellular V2X (C-V2X) and Intelligent Transportation Systems (ITS-G5) by spectrum sharing [2]. Given the virtual ubiquity of cellular infrastructure, C-V2X will enjoy all advantages of a commercial cellular network managed by MNOs. This way, the V2X roadside access could be handled with the same field equipment that is rolled out for cellular services. It thus puts at the disposal a technology platform which is scalable and evolvable and paves the road to 5G. C-V2X will use the same basic types of messages as ITS-G5, namely the Cooperative Awareness Messages (CAMs) and event-driven decentralized environmental notification messages. Unlike in ITS-G5, these links are controlled, enhanced, and completed by the cellular network (cellular assisted vehicular communications). This allows for quality of service control and offers seamless network access to all network resources, services, and content offered by the MNOs. Moreover, MNOs can define and offer specific services for road users and schedule radio and network resources according to their needs.

Road Traffic Situation Awareness and Cooperative Radar Sensing

The visionary aims of intelligent transportation systems are automated and connected driving, road safety, and traffic efficiency. Communication between cars and to the dedicated infrastructure in terms of messaging is one of the most important enablers for cooperative driving. The CAM massages enable gaining road traffic situation awareness in real time. However, it is restricted to appropriately equipped entities and relies on self-location of cars based on satellite and inertial navigation and map matching. While the automobile industry still uses the term "ego-car" to emphasize the autonomy and self-reliance of the car driver, it becomes obvious that more advanced cooperation, that includes exchanging information from all available sensors, like cameras, radar, and lidar, can significantly enhance road-traffic situation awareness. The reason for this is that distributed diverse sensing has a higher potential to detect and recognize other cars, obstacles, vulnerable road users, etc.

Efficient control and coordination of a certain traffic situation on intersections, roundabouts, ramps, bus stops, etc. would require some centralized data processing which collects information from all sensor carrying entities, condenses this information, and fuses it with information, which is available in the road-side units (RSU) from auxiliary sensors or from data bases (like maps). This control process estimates positions, predicts trajectories, and decides to transmit action messages to avoid accidents and optimize usage of traffic resources. Obviously, the quality of the Sensing, Communications and Fusion (SCF) process determines the achievable level of road traffic situation awareness. The computational resources, which are necessary for controlling cooperative driving, will come with the MEC as an integral part of the forthcoming 5G network. MEC has recently attracted considerable research interest for V2X communications [3]. The potential of MEC to support communications and computational tasks by offering edge computing resources and data off-loading for intelligent vehicle control and traffic management is just being demonstrated as a part of several field tests.

The trend towards automated and cooperative driving will lead towards a huge increase of sensor density. If we look more closely at radar, we observe that radar sensors do a very good job for Automatic Cruise Control (ACC) and collision avoidance. They can work over sufficiently long distances and under bad weather conditions, do not need visible light illumination, allow direct relative speed measurements (by Doppler shift processing) and provide overview coverage (without scanning). With the fast progress of millimeter-wave semiconductor and advanced packaging technologies, radar sensor modules became small and affordable. However, the current penetration rate is still low and mostly restricted to high-end cars and trucks. Future cars will have multiple radar systems on board to extend the field of view and the duty cycle will increase to cope with highly dynamic scenarios. Also, the installation of fixed radar sensors at intersections, bus stops, and other safety critical traffic hot spots is still in its infancy, which means that there is a huge potential for radar-sensing for intelligent traffic control, road safety, and other smart city applications not yet exploited. Therefore, it is more than reasonable to predict an exponential growth in radar sensor density. However, massive radar-sensing will cause a lot of interference and interoperability problems [4], [5]. Unfortunately, the well-established Frequency-Modulated Continuous Wave (FMCW) waveform is not well suited for interference mitigation. Of course, the directive antennas used in the typical frequency band of 76 to 81 GHz can help to reduce interference. Other mitigation concepts include frequency-hopping random chirp FMCW techniques. But this will not solve the problems when the density of radar increases as expected. There are also not so many chances to get new frequency bands for hosting more radar users since even in the millimeter-wave frequency region there is already an increasingly strong competition with communication systems.

The core problem of coexistence is that automotive radar does not include any advanced medium access control scheme (Radar-MAC). So the question arises: can radar borrow ideas for medium access control and radio resources scheduling from mobile radio?

Overview of Passive Coherent Location

Beyond the current hype of radar sensing for automotive and other industrial and security related civilian applications, radar has a long history in military and civilian air, space, and maritime surveillance. Although there are several parallels, radar and radio communications have developed separately in history and radio resources (frequency bands) are typically used in an exclusive and sometimes competitive way – with one remarkable exception, which is called passive radar or passive coherent location (PCL). Passive radar does not use a dedicated transmitter for target illumination. Instead, PCL uses transmitters of opportunity, which can be broadcast transmitters like DAB, DVB-T, or even FM radio. More recently, mobile radio including WiFi and cellular (mostly GSM and LTE) has been considered for PCL. Obviously, range coverage and resolution scale with transmit power and bandwidth which makes the applicable primary radio source dependent on the required target location performance. A topical overview on passive radar for civilian and military application is given in [6].

The basic PCL setup is depicted in Fig. 1. The observing radar node (PCL receiver/sensor) extracts the transmitted line of sight (LOS) signal as a reference and correlates it with the wave scattered off the target. The contour of constant excess delay of the target response relative to the LOS signal defines an ellipse, describing the possible positions of the target. Another pair of nodes would provide another ellipse, with their intersections indicating the potential positions of the target. It is well known that additional pairs of nodes can eliminate the inherent location ambiguity, add a further location dimension (x,y > x,y,z) and reduce errors in terms of variance or bias (e.g., in case of shadowed links). Obviously, the geometric arrangement of illuminating and observing nodes influences the resulting spatial location uncertainty distribution (some kind of geometric dilution of precision). Moreover, the target attitude (relative to illuminating and observing nodes) influences the detection probability because of the variability of the backscattered power (c.f. radar cross section). There is a basic difference between PCL and standard automotive radar. The latter is "monostatic" which means that the target is illuminated and observed by the same antenna, or by antennas that are almost at the same position (quasi-monostatic). The illumination and observation geometry of PCL is called bistatic or multistatic (in case of multiple illuminators and/or observers), also known as distributed MIMO radar [7].

As PCL relies on the ubiquitous available broadcast or cellular radio transmitters, it neither needs dedicated transmitters, nor additional frequency resources. Other basic features of PCL are summarized as follows. The reference link between the observing and the illuminating node should be LOS as only in this case the received signal suits as a geometrical reference. Moreover, it should have a high signal-to-noise ratio (SNR) and should not be distorted by multipath propagation. The preferred solution in existing PCL is to use a dedicated receiver link as indicated in Fig. 1. A high antenna directivity solves both problems. Another advantage of this solution is that it may relax some dynamic range requirements that arise if the distance to the target becomes big compared to the distance between observing and illuminating node. A multichannel array receiver is often proposed, which not only allows adaptive spatial filtering on the reference link but also perform direction of arrival (DoA) estimation of the scattered radar signal for better target location.

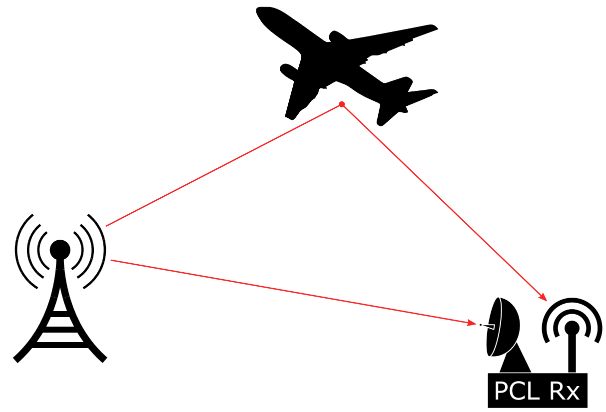


Fig. 1. The basic PCL setup consists of a transmitter of opportunity illuminating the target and a dedicated remote PCL sensor receiving the signal, which is backscattered from the target. An auxiliary directive antenna receives the pure LOS signal from the illuminator, which is used as correlation reference.

Cooperative Passive Coherent Location - Basic Concept

Given the state of the art as described above, let us ask ourselves: Can passive radar become an inherent service of a public mobile radio network? As with PCL, CPCL makes double use of the communication signals. However, contrary to PCL, in CPCL the radar sensors are not independent from the mobile communication network. The radar nodes are booked in as mobile terminals, i.e., user equipment (UE) devices. This offers a wealth of opportunities for co-operation between radar-UEs and the network. In CPCL, any radio node can act as an illuminator or observer. In road traffic scenarios, this may include both vehicles and fixed illuminators like roadside units (RSU) or base stations (e-node-B, eNB). In such a joint communication and radar network, cooperation has many facets. On the signal level, CPCL takes advantage of the mutual synchronization of all radio nodes involved, which maintains mutual orthogonality. Additionally, medium access control mechanisms minimize congestion, interference and collisions. Upcoming V2X communications will inherently submit cooperative vehicle status information such as precise position and speed which is needed for radar location and Doppler reference. Radio nodes can further cooperate by adjusting, respectively scheduling their radio resource parameters according to target location needs. Locally estimated target parameters can be exchanged by the same radio network and fused on a higher level. Generally speaking, CPCL can make use of all the network resources that will be made available in future mobile networks. This will make CPCL an unprecedented, powerful radar network.

Another facet of CPCL is its inherent resource efficiency. It makes dual-use of the allocated scarce frequency resources.

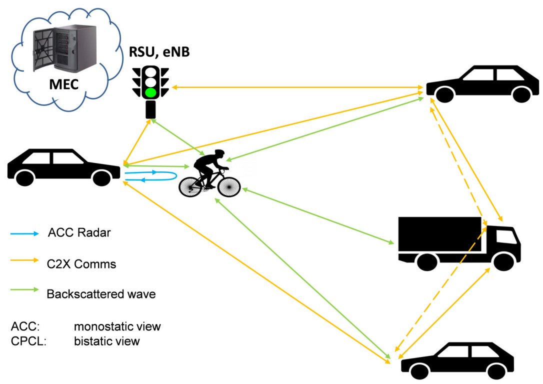


Fig. 2. CPCL – the Road Traffic Scenario. V2X communication signals of cars and roadside units (yellow arrows) illuminate the road user including those that are not equipped with V2X communications. All information available from the backscattered signals (green arrows) and from other sensors (such as ACC radar) together with a-priori information, e.g., from maps, is processed and fused in the MEC, which allows for a low latency service.

Also the radio system resources are dual-used, which reduces cost. Moreover, with the mobile radio network, an ubiquitous radar service will be available and CPCL coverage and performance will automatically develop with the installed network resources, which are continuously updated by the MNOs.

5G Key Enabling Technologies relevant for CPCL

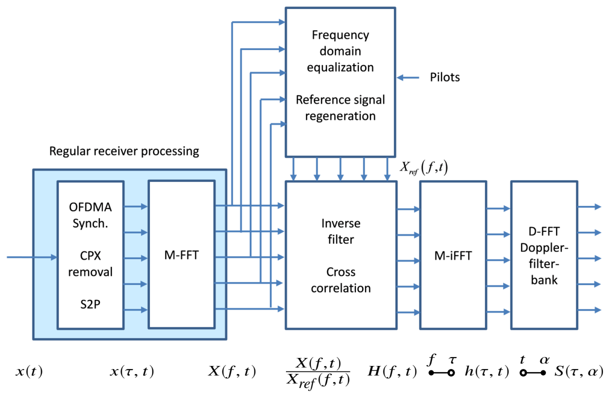
The features announced for C-V2X (see 3GPP release 14) will already widely support the CPCL idea. This holds even more true for the future 5G networks. The scalable radio access techniques based on orthogonal frequency division multiple access (OFDMA) and single carrier frequency division multiple access (SC-FDMA), as well as the upcoming generalized and filter bank-based versions [1] are very well suited for radar signal processing. V2V and V2I would support different MIMO radar setups where any radio node like the ones depicted in Fig. 2, can act as a radar node. This includes SIMO (from downlink communication), MISO (from uplink communication), and MIMO (from device-to-device and V2V communication). Channel bonding and carrier aggregation can deliver increased bandwidth and frequency diversity for enhanced range estimation. Even more bandwidth for very high range-resolution will be available at millimeter wave frequencies. If full-duplex transceivers appear, CPCL gains an extra monostatic property. Massive array beamforming will allow high-resolution spatial (directive) filtering and estimation. Finally, low latency communication and powerful computing resources in the MEC will support real-time interaction between cars and infrastructure and control of radar PHY-parameters in dynamic road traffic environments.

CPCL Challenges in Signal Processing, Data Fusion and Implementation

Although OFDM has been used as a wideband excitation signal for identification of time-variant multipath propagation (channel sounding) for many years [8], [9], it was only recently considered a favorable radar waveform. Moreover, OFDM is the native illumination waveform in case of PCL together with DVB-T, DAB, WLAN or LTE [10]. From frequency domain system identification, it is well known that periodic multi-frequency signals guarantee a leakage-free computation of the input and output signal spectra through fast Fourier transform (FFT), which stands for a low estimation variance of the frequency response function. This assumes that a cyclic prefix is applied and carrier orthogonality is maintained at the receiver. So, fortunately enough, for OFDM the basic assumptions of optimum signal processing in communications and radar coincide. This also includes other multicarrier waveforms like SC-FDMA, which maximize the achievable average output power for given power amplifier saturation level (minimum Peak to Average Power Ratio, PAPR).

However, as a communication signal is modulated by the information data stream, we do not a-priori know the transmit signal, which is needed as a correlation reference for radar signal processing. Fortunately, in a cooperative communication environment, all the advanced measures for robust signal reception, which have been developed for modern mobile radio during the last decades, can be applied for transmit signal recovery. So we don't need to apply an auxiliary reference receiver channel as shown in Fig. 1. Fig. 3 shows the basic receiver signal flow. OFDM based CPCL includes the standard signal processing chain of synchronization, cyclic prefix removal, FFT, channel estimation, and cyclic frequency domain equalization. Once the transmitted signal symbol is recovered (which is further supported by channel coding), the channel frequency response function is calculated symbol by symbol by inverse filtering. This is different from channel estimation applied for equalization, as it allows maximum consecutive symbol rate processing. It therefore not only enables Doppler shift estimation, but also maximum SNR gain by Doppler filtering. This filtering is implemented as another FFT filter bank (Doppler-FFT, D-FFT) along the so-called slow time axis, which eventually yields the complex joint delay-Doppler spreading function in Fig. 3. Hereby, we assume that the channel response factorizes with respect to time-delay and Doppler frequency, which requires the OFDM symbols to be shorter than the channel coherence time. This is usually the case in mobile radio. Target detection will be carried out in the magnitude-squared delay-Doppler (respectively range-Doppler) spreading function, which is known as scattering function. The respective maximum integration time, which corresponds to the slow time D-FFT-window, is limited by the moving speed of the target and the respective change in delay relative to the width of any delay bin on the fast time axis (delay time). Maximizing the integration time allows SNR gain and, hence, better detection of weaker target returns in noise. This type of Doppler shift processing is the key to separating the signals scattered back from the moving targets from those of the static environment. Unfortunately, the desired target echoes are typically much weaker than the static clutter. Therefore, we need more dynamic range in the channel impulse response for CPCL than for data transmission.

A specific problem arises from the multiuser resource allocation in the LTE radio frame in frequency and time



CPX: Cyclic prefix
S2P: Serial to parallel
t: Slow time
τ: Fast time
α: Doppler frequency

$X_{ref}(f,t)$: Transmitted signal (correlation reference)
$x(t)$: Received input signal
$H(f,t)$: Frequency response (time variant)
$h(\tau,t)$: Impulse response (time variant)
$S(\tau,\alpha)$: Delay-Doppler-Spreading function

Fig. 3. OFDM signal processing scheme for estimation in the joint delay-Doppler domain.

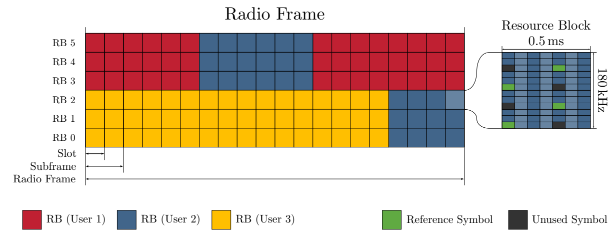


Fig. 4. Example physical resource block distribution (frequency-time resource grid) of three users (marked by different colors) in a LTE radio frame of 10 ms length and 1.4 MHz bandwidth. The close-up in the right-hand panel shows the internal structure of the resource blocks.

because of OFDMA as illustrated by Fig. 4. If the radio frame would be occupied uniformly by Physical Resource Blocks (PRBs) belonging to a single user only, the magnitude-squared ambiguity function would be sinc-squared in the range and Doppler domains. However, in the multiuser case, the PRBs for any user are distributed more or less sparsely and multiple users are interleaved in frequency and time. There can even be blanks. In case of a downlink-radar (eNB to UE), any radar-UE could perhaps process the full OFDMA symbol. For an uplink-Radar (UE to eNB) there is no such chance. Although, thanks to time advance synchronization, the eNB would receive one composite OFDM symbol and process it by one FFT, the delay-IFFT can only process the PRBs belonging to one radar-UE. The parts of the PRB, which belong to other UEs in the up-link, have to be considered as a separate measurement. The resulting sparse occupation in the frequency-time plane would seriously degrade the shape of the resulting ambiguity function. Hence, more sophisticated range-Doppler parameter estimation procedures are required. One option would be sparse reconstruction based on compressive sensing schemes. Another one is model-based parameter estimation, e.g. as described in [8], [11], [12]. The latter needs a physically motivated parametric data model to represent both the multipath propagation as well as the instrument function of the device signal processing chain, which can be determined by calibration. This data model would effectively interpolate the missing samples in the sparse frequency-time resource grid and extrapolate it allowing for high resolution in the delay/Doppler plane beyond Rayleigh resolution.

However, the challenges, mentioned above shortly, are only the tip of the iceberg. There is a tremendous amount of open research questions. Here we can only provide a short overview.

Radar Signal Processing

CPCL represents a distributed MIMO radar network in which both the illuminator, the sensor, as well as the target can be moving. This means that the clutter originating from the predominantly static environment may have Doppler shift. The separation of target signal returns from clutter may be enhanced by estimating target tracks or inherent target temporal variability (micro Doppler signature). Target tracking will be supported if dynamic target parameters such as speed vectors beyond mere instantaneous location are estimated. Spatial, frequency, and temporal (over slow time) diversity can be exploited to further enhance detection probability. Spatial and frequency resources can be locally concatenating or widely distributed. This means co-located antennas (respectively antenna arrays) versus multiple distributed radar-UEs, which is a multiple bi-static (respectively multi-static) radar geometry. In terms of frequencies, it means bonding of neighboring frequency channels or aggregation of widely fragmented bands. The concatenated bands may be mutually coherent or non-coherent. The inherent aspect-angle variability of distributed MIMO radar provides us with a spatial diversity gain that is related to the bi-static radar cross section (RCS), which is considered a multivariate statistical parameter. Therefore, CPCL radar requires advanced distributed detection and estimation schemes that exploits resource and target sparsity, diversity, and dynamics.

Network, Signaling, Synchronization, and Hardware Issues

There are many research questions related to radio design, such as maximizing the receiver dynamic range as weak radar echoes have to be identified in the presence of strong LOS signals. Massive array beamforming will support LOS reference signal extraction by multipath filtering, relax dynamic range problems, and allow DoA estimation for target location. The millimeter wave bands envisaged for 5G will offer bandwidths comparable to those of current automotive radars. In terms of the radio network, CPCL could use both eNBs or UEs as illuminators, resulting in SIMO or MISO radar networks. Direct cooperation of multiple eNBs or UEs would allow building MIMO radar networks. Optimum design rules and achievable performance figures are unknown at present. This holds true if we compare upcoming 5G and G5 for the case of V2V. The fully synchronous, eNB controlled, and inherently parallel operation of multiple moving radar UEs in 5G will be a big advantage.

Communication vs. Radar Resource Scheduling

CPCL will develop its highest potential if the radio resources would be allocated in a suitable way to adapt and optimize the joint radar- and communication-performance. This would include choosing the proper PRB-distribution in time and frequency, allocation of multiple (perhaps non-consecutive) radio bands, predistortion, and allocation of spatial resources. If CPCL were available as a network service, radar channel quality indicator (CQI) feedback would be required for controlling the radar parameters. The definition of radar quality-of-service (QoS) and CQI, knowledge about competition versus coincidence of communication, and radar QoS, etc., are open questions. For instance, well-known capacity maximizing OFDM subcarrier power allocation schemes like water filling and worst subcarrier avoiding (WSA) algorithms have already found their equivalence in multiple and extended target tracking MIMO radar [13]. Specific procedures will be applicable if spatial precoding is involved. Without centrally controlled resource scheduling, for example in 802.11p or LTE-V (in case of missing cellular coverage), distributed MAC mechanisms would need to coordinate radar and communication resources accordingly.

Data Fusion

CPCL inherently is a multi-sensor technology. This means that a wide variety of measurements is available, which have different uncertainty characteristics and diverse impact to achieve a certain platform mission. The key estimation procedures will rely on Bayesian data fusion, multiple hypothesis estimation, and tracking [14]. This requires different levels of data fusion ranging from fusion of local platform data to distributed fusion, and dynamic scene analysis at critical traffic hot spots, e.g., cross-roads. Real-time map services will submit precise location information of static objects usable as reference landmarks for CPCL calibration. The use of the real-time computing facilities of the MEC for CPCL distributed data fusion, sensor resource allocation, and sensor mission control will be a challenging field of research towards an adaptive, perhaps cognitive radar network. The MEC also bridges the gap between the "local awareness bubble" to the global information in the internet and to the higher geographical layers of traffic control. So it paves the way from local CPCL to global information fusion for street traffic control and smart cities.

Initial Measured Example

In the following, we present preliminary results from an initial measurement campaign of a bi-static radar scenario with one illuminator (Tx) and two sensors (Rx) as shown in Fig. 5a. In this simple example, both Tx and Rx were stationary and only the target car was moving. The measurement was carried out by using three software defined radio modules of the type USRP X310 (one as transmitter, additional power amplifier 33 dBm; two as receivers, synchronized by GPSDO). The signal bandwidth was 80 MHz. The slow time versus delay response as depicted in Fig. 5b is dominated by the LOS signal and strong static clutter. The magnitude-squared Doppler-delay responses (scattering functions) in Fig. 5c and 5d are calculated by a 10 ms FFT (D-FFT) along slow time. Whereas the moving car cannot be seen in Fig. 5b because of the dominating static clutter, it becomes clearly visible at the respective bi-static Doppler-delay-bin (360 Hz and 201.1 ns in Fig. 5c and 340 Hz and 182.2 ns in Fig. 5d). An additional high-resolution processing step was applied to estimate and remove the LOS path and the strongest reflection at 58.2 ns and 227.4 ns in Fig. 5c and 81.9 ns and 259.7 ns in Fig. 5d, respectively. This example clearly shows that static clutter removal would need well-defined signal processing measures which exploit the dedicated Doppler shift of the target. High-resolution parameter estimation can further enhance static and dynamic target location and clutter removal.

Conclusion and Outlook

Although the dictum of this paper was driven by requirements from the automotive sector, it becomes obvious that there may be other vertical markets related to mobility, security, and industrial areas, where an integrated communications and radar service could be a great benefit. CPCL will take advantage of the main features announced for 5G. Of course, as a new service, it will increase the network traffic. However, at the same time it reuses the communication signals for radar, thus eventually saving resources. Hence, it may be seen as a resource saving green technology. The advantage as seen from the radar point of view is that a CPCL service may have access to all radio frequencies assigned for mobile services. This opens a huge potential for radar frequency diversity. It may even solve the competition issue in frequency assignment between radar and communication community. Therefore, we deem that CPCL is an extremely promising opportunity to build a very powerful, distributed MIMO radar system on an unprecedented service level as a part of the public mobile radio network. The service potential of CPCL comes from the fact that it exploits newest radio communication principles developed throughout an unrestrained progress in mobile radio over the last decades. It is an overdue chance for building a flexible and adaptive radar network with ubiquitous availability.

Compared to simple passive radar, CPCL has many advantages, which we have discussed in this paper. Among those are completely orthogonal operation (also for multiple sensors) which reduces estimation variance, access to the whole variety of frequencies and waveforms, and the availability of massive spatial processing resources. Compared to dedicated radar systems, we have all facilities at hand to build netted SIMO, MISO, or MIMO radar networks, with all radar interference problems solved by a highly developed radio MAC and with the inherent potential of intelligent and cognitive access and data processing. Many beneficial features are related to the efficient, software defined use of 5G radio and network resources for radar processing and data fusion based on real-time MEC computation facilities. Of course, there are many open, yet interesting research questions to be solved step by step in order to make CPCL a successful service within 5G.

We eventually deem that CPCL could be a service that may be offered by the mobile network operators (MNO) to public user groups and public safety agencies, e.g., for road traffic monitoring, logistics, mobility and several security applications, as it is likely that 5G networks will play a more

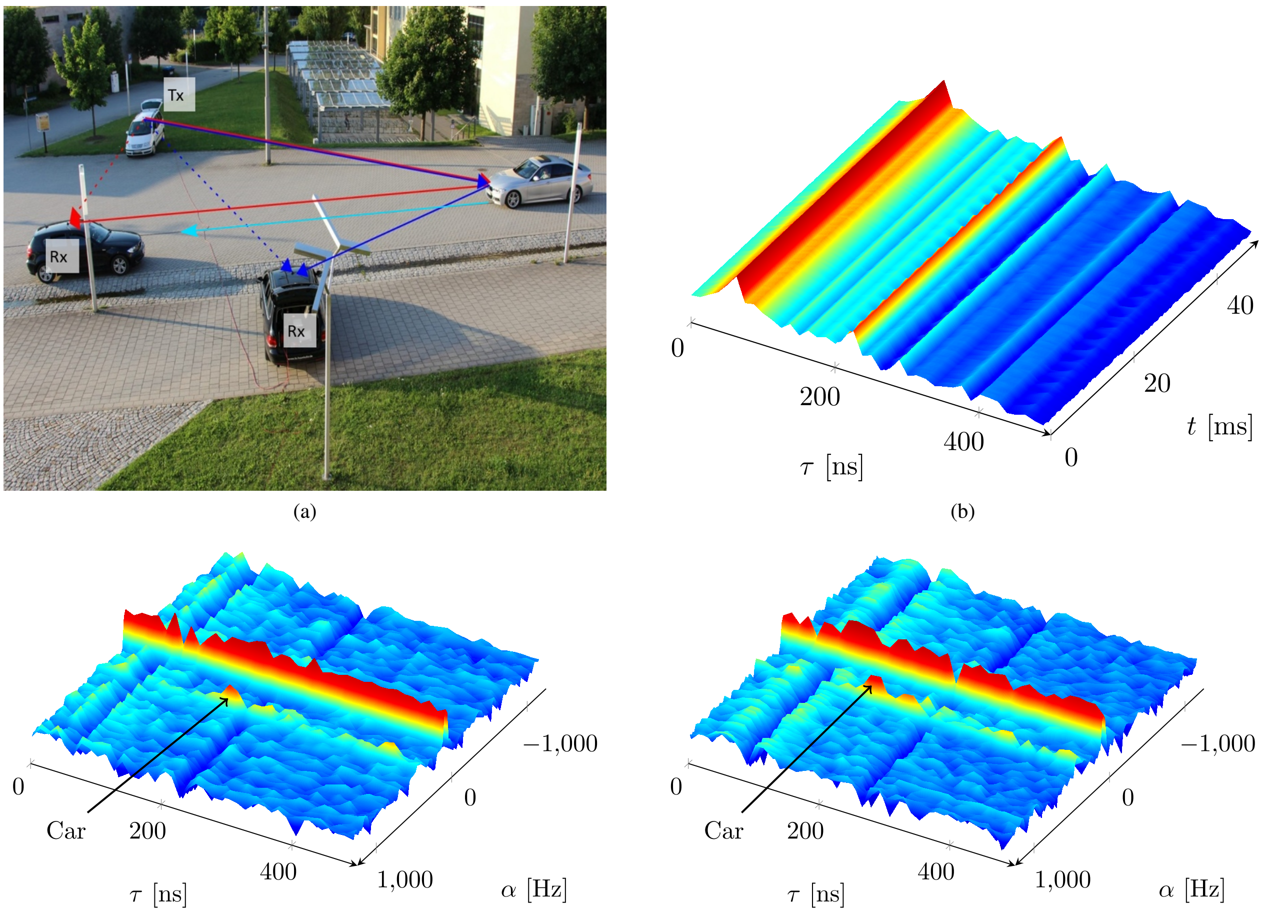


Fig. 5. Measurement setup and results: a) Bi-static radar scenario. Car 1 acts as illuminator (Tx), whereas car 2 and 3 are sensors (Rx). The right car is the target, driving along the light blue arrow. b) Slow time (t) vs. fast time (τ) response at car 2; c) Doppler (α) vs. fast time (τ) response at car 2; d) Doppler (α) vs. fast time (τ) response at car 3

important role for safety and mission critical communication than earlier mobile radio generations [15]. We thoroughly believe that there might be a MNO business model behind CPCL.

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