OpenAirInterface: A Flexible Platform for 5G Research

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ABSTRACT

Driven by the need to cope with exponentially growing mobile data traffic and to support new traffic types from massive numbers of machine-type devices, academia and industry are thinking beyond the current generation of mobile cellular networks to chalk a path towards fifth generation (5G) mobile networks. Several new approaches and technologies are being considered as potential elements making up such a future mobile network, including cloud RANs, application of SDN principles, exploiting new and unused portions of spectrum, use of massive MIMO and full-duplex communications. Research on these technologies requires realistic and flexible experimentation platforms that offer a wide range of experimentation modes from real-world experimentation to controlled and scalable evaluations while at the same time retaining backward compatibility with current generation systems. Towards this end, we present OpenAirInterface (OAI) as a suitably flexible platform. In addition, we discuss the use of OAI in the context of several widely mentioned 5G research directions.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*

General Terms

Experimentation, Performance, Measurement

Keywords

OpenAirInterface; 4G/5G mobile networks; LTE; Experimentation; Emulation; Software-defined radio (SDR) platform

1. INTRODUCTION

Rapidly growing mobile data traffic fuelled by wide adoption of Internet connected mobile devices (smartphones, tablets, etc.) and expected dramatic increase in the number of connected devices with different traffic patterns from personal communication devices has created a vast field for innovation in terms of mobile broadband protocols, algorithms, architecture, and services. So, while 4G Long Term Evolution (LTE) networks are being rolled out worldwide, research for the next generation mobile networks has already begun with the examination and evaluation of candidate technologies and architectures [1, 2, 3, 4]. Given the practical requirement for backward compatibility between successive technologies, it is rational to assume that these technologies, often referred to as 5G or Beyond 4th Generation (B4G), will naturally evolve as an extension to LTE with newer and advanced features.

Performance assessment of candidate innovations over LTE and post-LTE technologies requires rigorous evaluation and real-world validation prior to deployment. While network simulation software has evolved significantly over the years, it still cannot capture the complex real world environment well, and real/field experimentation is still considered essential, especially at the later stages of technology development. Real-world experimentation over testbeds with commercial LTE equipment, however, restrict configuration capabilities, flexible deployment and extension to a certain extent due to constraints imposed by operators and large vendors, mainly commercial considerations. This has resulted in the need for an open and flexible LTE centric experimentation platform with a high degree of realism that the community can commonly use for understanding the complexities associated with real world settings while at the same time obtain reproducible and verifiable results, all with the same ultimate aim of developing effective and future-oriented system architectures and technologies.

In this paper, we provide an overview of the OpenAirInterface (OAI) [5] platform that we believe is best placed to fulfil the above mentioned need for an open and flexible 4G/5G experimentation platform. OAI is based on a PC hosted software radio frontend architecture. It comes with an open-source and complete 3GPP standards compliant software implementation of LTE and LTE-Advanced features. The OAI spans the two main components of the LTE system architecture: (1) the Evolved Universal Terrestrial Radio Access Network (E-UTRAN); and (2) the Evolved Packet Core (EPC). It also covers the entire protocol stack from the physical to the networking layer. It also offers highly realistic emulation modes. As a result, the OAI platform can be used for indoor/outdoor field experimentation or controlled/scalable evaluations with emulated wireless links. Based on the successful OpenAirInterface initiative (counting more than 3000 members), the platform also offers an open-source platform facility for remote experimentation with LTE via the EU FLEX project[1].

To demonstrate the value of OAI for 5G related studies, we present two case studies using OAI, one on machine-to-machine (M2M) communication and the other on cloud RANs (C-RANs). We also discuss its use for a few other 5G research areas actively being investigated in the community, including device-to-device communications, software-defined mobile networks, and novel uses of spectrum.

2. OPENAIRINTERFACE (OAI)

OpenAirInterface (OAI) [5] is an open experimentation and prototyping platform created by the Mobile Communications Department at EURECOM to enable innovation in the area of mobile/wireless

[1] http://flex-project.eu/

networking and communications. With OAI, the transceiver functionality (of a base station, access point, mobile terminal, core network, etc.) is realized via a software radio front end connected to a host computer for processing; this approach is similar to other widely used software-defined radio (SDR) prototyping platforms in the wireless networking research community such as SORA [6]. To the best of our knowledge, OpenAirInterface is the only SDR based solution that is fully open-source and provides a complete software implementation of all elements of the 4G LTE system architecture — user equipment (UE), eNodeB (eNB), and the core network. Among the existing alternatives, the one that comes nearest in terms of functionality is LTE 100, a commercial and closed-source development from Amarisoft [7]; it provides eNB and core network functionality for use over a standard Linux-based PC interfaced with a USRP SDR platform.

Two unique features of the OAI platform are:

1. An open-source software implementation of the 4th generation (4G) mobile cellular system that is fully compliant with the 3GPP LTE standards and can be used for real-time indoor/outdoor experimentation and demonstration.
2. Built-in emulation capability that can be used within the same real execution environment to seamlessly transition between real experimentation and repeatable, scalable emulation. Specifically, two physical layer (PHY) emulation modes are supported which differ in the level of detail at which PHY is realized.

The rest of this section describes the software, hardware and emulation features of OAI.

2.1 Software

Currently, the OAI platform includes a full software implementation of 4th generation mobile cellular systems compliant with 3GPP LTE standards in C under realtime Linux optimized for x86.

At the physical layer, it provides the following features:

- LTE release 8.6, with a subset of Release 10;
- FDD and TDD configurations in 5, 10, and 20 MHz bandwidth;
- Transmission mode: 1 (SISO), and 2, 4, 5, and 6 (MIMO 2x2);
- CQI/PMI reporting;
- All DL channels are supported: PSS, SSS, PBCH, PCFICH, PHICH, PDCCH, PDSCH, PMCH;
- All UL channels are supported: PRACH, PUSCH, PUCCH, SRS, DRS;
- HARQ support (UL and DL);
- Highly optimized baseband processing (including turbo decoder).

For the 3GPP LTE Access-Stratum, standard-compliant (Release 8 and Release 10) implementations of PHY, MAC, RLC, PDCP and RRC, spanning the entire protocol stack from the physical to the networking layer, for both eNB and UE and in both FDD and TDD. Specifically, the access network (E-UTRAN) protocol stack implementation in the OAI provides:

- LTE release 8.6 and a subset of Release 10 features;
- Implements the MAC, RLC, PDCP and RRC layers;
- Protocol service for Release 10 eMBMS (MCH, MCCH, MTCH)
- Priority-based MAC scheduler with dynamic MCS selection;
- Fully reconfigurable protocol stack;
- Integrity check and encryption using the AES and Snow3G algorithms;
- Support of RRC measurement with measurement gap;
- Standard S1AP and GTP-U interfaces to the Core Network;
- IPv4 and IPv6 support.

Moving to the core network, the OAI also comprises of standard-compliant (Release 9 and Release 10) implementations of a subset of 3GPP LTE EPC component with the Serving Gateway (S-GW), the Packet Data Network Gateway (P-GW), the Mobility Management Entity (MME), the Home Subscriber Server (HSS) and the Non-Access Stratum (NAS) protocols. Features of the OAI EPC implementation include:

- S-GW, P-GW, MME and HSS implementations. The OAI reuses standards compliant stacks of GTPv1u and GTPv2c application protocols from the open-source software implementation of EPC called nwEPC [8];
- NAS integrity and encryption using the AES and Snow3G algorithms;
- UE handling procedures: attach, authentication, service access, radio bearer establishment;
- Transparent access to the IP network (no external S-GW or P-GW are necessary). Configurable access point name, IP range, DNS and E-RAB QoS;
- IPv4 and IPv6 support.

Figure 1 shows a schematic of the implemented LTE software in the OAI. It comes with a rich software development environment with Aeroflex-Geisler LEON / GRLIB, RTAI, Linux, GNU, Wireshark, control and monitoring tools, message and time analyzer, low-level log processing, traffic generator, profiling tools and soft scope. It also provides tools for protocol validation, performance evaluation and pre-deployment system test [5].

2.2 Hardware

For real-world experimentation and validation, the default software radio frontend for the OAI is ExpressMIMO2 PCI Express (PCIe) board. This board features a LEON3 embedded system based on Spartan 6 LX150T FPGA as well as 4 high-quality RF chipsets from Lime Micro Systems (LMS6002), which are LTE-grade MIMO RF front-ends for small cell eNBs. It supports stand-alone operation at low-power levels (maximum 0 dBm transmit power per channel) simply by connecting an antenna to the board. External RF for high-power and TDD/FDD duplexing can be connected to ExpressMIMO2 depending on the deployment scenario. RF equipment can be configured for both TDD or FDD operation with channel bandwidths up to 20 MHz across a wide spectrum range (250 MHz-3.8 GHz) and a subset of LTE MIMO transmission modes. ExpressMIMO2 boards are reasonably priced and completely open (GNU GPL), both at the hardware and software level.

The embedded software for the FPGA can be booted via the PC or can reside entirely in the boot ROM which is part of the FPGA design. In the current design, the embedded software is booted by PCIexpress dynamically under control of the PC device driver. The basic design does not include any on-FPGA signal processing and consumes approximately 10-15% of the FPGA resources. So there is significant room left for additional processing on the FPGA, for instance Xilinx FFT processors to offload some processing from the host PC if required.

Figure 1 shows the the entire LTE software stack on the top of the ExpressMIMO2 platform. Several interoperability tests have been successfully performed with commercial mobile terminals, namely

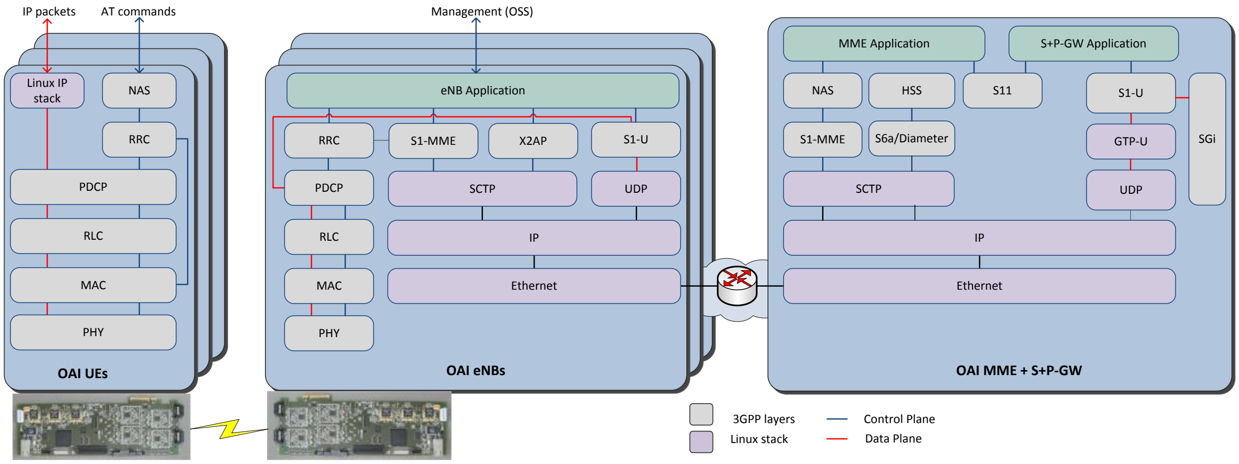

Figure 1: OpenAirInterface LTE software stack over ExpressMIMO2 software radio frontend.

off-the-self commercial LTE UEs (e.g., Huawei E392 USB dongles) and smartphones, as well as with commercial 3rd party EPC prototypes. The OAI platform can be used in several different configurations involving commercial components to varying degrees:

1. OAI UE ↔ OAI eNB + OAI EPC
2. OAI UE ↔ OAI eNB + Commercial EPC
3. OAI UE ↔ Commercial eNB + OAI EPC
4. OAI UE ↔ Commercial eNB + Commercial EPC
5. Commercial UE ↔ Commercial eNB + OAI EPC
6. Commercial UE ↔ OAI eNB + Commercial EPC
7. Commercial UE ↔ OAI eNB + OAI EPC

Besides ExpressMIMO2, the OAI now supports the USRP Hardware Driver software (UHD) for use with the recent versions of USRP PC-hosted software radio platforms that are widely used in the research community. Based on the initial efforts by Agilent China, the OpenAirInterface soft modem software has been successfully interconnected with a USRP B210 platform. This development is now delivered as part of the publicly available software package from the OAI website and SVN server [5]. EURECOM will continue to maintain this development and extend it to X300 (USRP-Rio) family of products. This achievement validates the standard PC plus generic SDR frontend approach taken in OAI since the code has been independently ported on a totally different hardware target.

2.3 Emulation

Besides the real-time operation of the OAI software LTE platform over the hardware targets described above, the full protocol stack can be run in a controlled laboratory environment in emulation mode for realistic validation and performance evaluation of innovations from both system and link level perspectives. This emulation capability is designed to represent the behavior of the wireless access technology in a real network setting while respecting the temporal frame timing of the air-interface.

Two different emulation modes are provided to realize the behavior of the wireless medium: (1) *PHY Abstraction mode* that relies on a PHY abstraction unit which simulates error events in the channel decoder; (2) A more detailed and computationally intensive *Full PHY Layer mode* that involves convolution of the real PHY signal with an emulated channel in real-time. The platform can be run with either of these two emulation modes. The remainder of the protocol stack for each node instance uses the same implementation, as would be in the full system. Each node has its own IP interface that can be connected either to a real application or a traffic generator.

The emulator also implements the 3GPP channel models each comprising of three components (path loss, shadow fading and stochastic small scale fading) and interacts with the mobility generator to perform different channel realizations over time with interference. Multiple node instances can be run on a single PC with this emulation capability, permitting large-scale and repeatable in-lab system evaluation. The emulation capability can also be used for controlled testing of a system prototype prior to its deployment in a real RF environment.

2.4 Comparison of OAI with Other Platforms and Approaches

We now briefly discuss other alternative evaluation approaches and tools with the view of highlighting the distinctive aspects of OAI. One approach is to deploy testbeds with commercial LTE gear (eNBs, UEs, EPC) with open access for experimentation (e.g., CREW project[2]). Main downsides of this approach are that it does not offer the desired level of flexibility and is also expensive to deploy.

System-level simulation [9] is an alternative and a more common approach in which some or all of the system and network stack is modeled. Some tools within this approach are analytical in nature with no notion of time and are typically implemented in MATLAB (e.g., [10]). Others are packet-oriented network simulators based on discrete-event simulation. These simulators rely on a logical clock and either model the protocol layers or abstract out some of them altogether. Examples include LENA[3] (now integrated into ns-3), LTE-Sim [11] and SimuLTE[4]. In contrast, OAI implements the full protocol stack to run on a real execution environment respecting frame timing constraints. As a result, it is a more realistic platform (even in emulation mode) compared to the most detailed of simulators from those mentioned above.

Another approach that is getting increasingly popular and which OAI follows is the use of SDR based platforms for greater level of flexibility and realism. There are several projects focusing on software implementation of LTE over the popular USRP platform (e.g.,

[2] http://www.crew-project.eu/easyc
[3] http://networks.cttc.es/mobile-networks/software-tools/lena/
[4] http://simulte.com/

LTEENB[5], OpenLTE[6], gr-lte[7], OLSD[8]). Among these, LTEENB comes closest to OAI in terms of complete implementation and emulation capabilities but it is not open (commercialized by Amarisoft [7]). WARP [12] and SORA [6] are also widely used platforms in the wireless networking research community but they are mostly oriented towards 802.11. SORA, though not truly open-source, is closer to OAI in that it comes with partial LTE support and emulation capability via the Colombo SDK[9]. There are also other commercial SDR based soft LTE implementations (e.g., Nutaq PicoSDR[10]). OpenEPC[11] is a 3GPP compliant EPC implementation with an open interface but not open-source. Compared to the above, the OAI has two unique features as mentioned at the beginning of this section: (1) SDR based full software implementation of LTE that is open-source and standard compliant; (2) Highly realistic emulation capability that enables repeatable and scalable system evaluations. OAI community is also growing rapidly with several active research projects and 30 academic/industrial research labs using it.

3. 5G RESEARCH DIRECTIONS AND OAI

We believe that OAI can be instrumental in the development of the key 5G technologies. It provides researchers with an environment in which they can rapidly prototype and test systems which would be infeasible with proprietary equipment. Here we consider a selection of 5G research directions [1, 2, 3, 4] and discuss the use of OAI in addressing related research questions.

3.1 Machine-to-Machine (M2M) Communication

M2M communication is expected to enable the Internet of things where billions of devices, typically low power devices requiring low data rates, work with little or no human intervention. LTE/LTE-A and future cellular networks are expected to connect a new generation of such M2M devices. However, the majority of current wireless systems, including LTE/LTE-A, are designed to support a small number of personal mobile communication devices with a continuous flow of information, at least in terms of the time-scales needed to send several IP packets (often small control information and large data for user-plane data) containing information, such that the induced signaling overhead is manageable. While these systems are intended mostly for downlink-dominant and bursty traffic, emerging application scenarios found in M2M communication as well as in online interactive gaming, and social networking/messaging generally have different characteristics, namely: massive numbers of devices, uplink dominant traffic often periodic and non-realtime, and small and low duty cycle packets.

Here we present a case study of OAI that highlights the value of choosing a suitable channel access method to serve M2M traffic. Specifically we consider a grant-free contention-based channel access (CBA) paradigm in which common resources are allocated on a per group basis to radically improve the efficiency of uplink channel access and enable massive number of connected devices. The distinctive feature of CBA is that the resource allocation is not UE-specific but on a group basis, thus the signaling overhead caused by dedicated channel access is bypassed, allowing UEs to pseudo-randomly send packets on the common resources.

The above mentioned CBA method is implemented in the OAI platform as a complementary uplink channel access method alongside the regular access method. The scheduler is also extended to allocate resources both on a per-user and a per-group basis. We have conducted an extensive set of experiments with the OAI configured to operate in LTE/LTE-A Release 10, TDD configuration 3 for 5MHz channel. The performance of the grant-free channel access relative to regular scheduling is evaluated under three different types of constant bit rate (CBR) traffic patterns: (1) small packet CBR (SCBR) with 32 byte packets and mean packet inter-arrival time of 1000ms; (2) medium packet CBR (MCBR) with 64 byte packets and mean packet inter-arrival time of 500ms; (3) big packet CBR (BCBR) with 128 byte packets and mean packet inter-arrival time of 100ms. Note that SCBR and MCBR traffic patterns are more representative of the machine-type communication whereas BCBR captures conventional human-type communication.

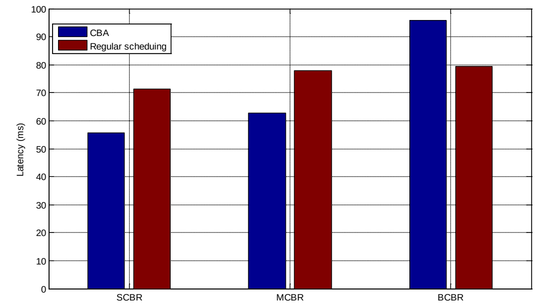

Figure 2: Measured latency using OAI for contention-based uplink channel access (targeted towards machine-type communication) relative to regular scheduling under three different traffic patterns: small packet CBR (SCBR), medium packet CBR (MCBR) and big packet CBR (BCBR).

Figure 2 shows a snippet of results comparing the two access methods with respect to the average one-way end-to-end delay in the uplink direction (i.e., from the devices to the application server). It can be seen that grant-free channel access outperforms the regular scheduling for lighter traffic patterns (SCBR and MCBR) as collision rate with CBA stays low (less than 15%) and it can thus gain by bypassing the redundant signaling required by the regular scheduling. On the other hand, regular scheduling does better for BCBR traffic. This is because the collision rate among different UEs when using the CBA increases with the increasing packet generation rate (i.e., increasing packet size and packet arrival rate) and is fairly high with BCBR traffic, ranging from 15% to 25%; the parameters of the CBA method are also optimized for light and sporadic traffic patterns. We also find that the induced latency is also dependent on eNB configuration (e.g., frame configuration and scheduling request periodicity), joint user and group based resource allocation policy, backoff timer for the grant-free access, and the number of the groups among others (results not included for brevity).

3.2 Cloud RAN (C-RAN)

C-RAN systems replace traditional base stations with distributed radio elements connected to a centralized baseband processing pool [2]. The decoupling of the radio elements from the processing serves two main purposes. Centralized processing reduces the required redundancy, improving the overall efficiency of the network. The remote radio heads have a much smaller footprint than a base station with on site processing, allowing for simpler and cost-effective network densification.

[5] http://bellard.org/lte/
[6] http://sourceforge.net/projects/openlte/
[7] https://github.com/kit-cel/gr-lte
[8] https://sites.google.com/site/osldproject/
[9] http://research.microsoft.com/en-us/projects/colombosdk/
[10] http://nutaq.com/en/products/picosdr
[11] http://www.openepc.net/

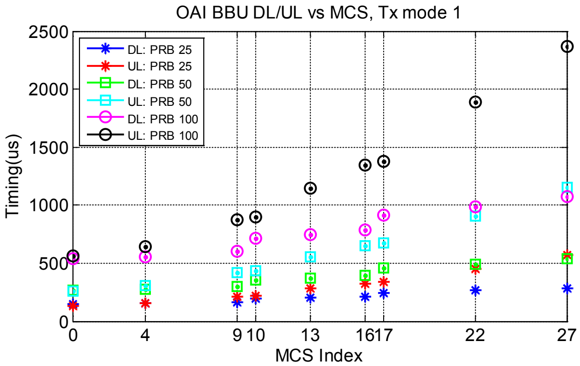

Figure 3: Results of profiling OAI baseband functions from a C-RAN perspective.

Research into C-RAN centers around resource and energy optimization. Centralized processing combined with network function virtualization (NFV) opens the door to optimizations such as load balancing which, while common in other networks, are new to the cellular edge. Realizing such optimizations, however, requires addressing several challenges, arising from the need to meet tight timing requirements. Another important area of research for C-RAN is its role as a supporting technology for other new developments. For example, the centralization of processing C-RANs eases the signalling requirements to support advanced techniques such as coordinated multi-point (CoMP) transmissions.

The OAI provides a complete implementation of the LTE protocol stack upon which different C-RAN testbeds can be built. As examples, we can highlight the joint collaboration between China Mobile, Agilent (China) and IBM (China) to build a so-called C RAN prototype B as well as the profiling of the baseband functions by Bell Labs India and Alcatel France [13]. To demonstrate the OAI usage in the C-RAN context, we present here our recent results profiling the OAI physical layer under different parameters with the goal of provisioning computing resources and exploiting the load variation across base stations (BSs) with a statistical guarantee to meet the realtime requirements.

Figure 3 shows a sample of profiling results obtained from the OAI to perform downlink (DL) and uplink (UL) baseband processing as a function of allocated physical resource blocks (PRBs), modulation and coding scheme (MCS), and the minimum SNR for the allocated MCS for 75% reliability across 4 rounds of HARQ. The results are obtained for a single user, SISO mode, AWGN channel, and full buffer (ranging from 0.6 for MCS 0 to 64Mbps for MCS 28) in both directions. The experiment is performed using GCC 4.7.3, x86-64 (3 GHz Intel Xeon E5-1607), using a single process bound to a particular CPU (processor affinity). It can be observed that the processing load increases with the increase of PRB and MCS, and that it is mainly dominated by the Rx chain (UL). Furthermore, the gap between the Tx and Rx processing time also increases with the increase of PRB and MCS for the full buffer scenario. Additional experimentation has revealed that the layer 2 processing is also non-negligible and sharply increases with the increase of users, traffic load, and scheduling policy.

By analyzing the processing for a 1ms LTE sub-frame, the main conclusion that can be drawn is that we require 1 processor core (on average) for the receiver processing assuming 16-QAM in uplink and approximately 1 core for the transmitter assuming 64-QAM in downlink, making it necessary to have 2 cores to handle processing of an eNB instance. But note that these measurements were done without the current generation of AVX2 instructions. With the optimizations for this latest architecture, the computational efficiency is expected to double and thus a full software solution would fit with an average of 1x86 core per eNB instance.

3.3 Heterogeneous Cellular Networks and Device to Device (D2D) Communication

It is widely recognized that future mobile networks will be highly heterogeneous consisting of small cells and relays. The OAI platform makes it straightforward to create such heterogeneous network (HetNet) scenarios. So it can be used to study pertinent research issues, including: inter-tier and inter-cell interference in small cells; and quantifying the benefit of enhanced small cells using the new carrier type [4].

D2D communication is a new entrant to the increasingly heterogeneous mobile networks landscape. The fact that the OAI provides terminal, base station (BS), and core network implementations, allowing researchers to test all sides, is of particular importance for determining the role of the BS in device discovery and connection initiation in D2D communication. With D2D communication, researchers need to assess whether UEs can work directly with each other or whether control signalling would still be required from the BS (e.g., to avoid intra-cell interference). Such assessments and issues related to the optimal/local routing and caching, in particular at the base station, can be easily realized and experimented with the OAI. The flexibility that OAI provides to also work with commercially available mobile terminals (UEs) with D2D support will be highly beneficial for testing interference management and backward compatibility.

3.4 Shared Spectrum and Millimeter Waves

Increasing the available spectrum and making efficient use of existing spectrum are part of yet another strategy to cope with the exponentially growing mobile data traffic. According to some studies, 1.2–1.7 GHz of new spectrum is required to meet the rising capacity demands and a large part of that new spectrum may be "shared" with a primary user owning the spectrum but secondary use is allowed following one of several possible spectrum sharing models [14]. As the OAI can operate over a wide range of frequencies, and given its open, complete and software LTE implementation, it is well positioned as an experimental platform for addressing spectrum sharing related research issues; examining relative merits of different dynamic spectrum access (DSA) models (e.g., licensed shared access (LSA)) and mechanisms (e.g., geolocation databases, spectrum sensing); aggregated use of disparate and diverse spectrum bands leveraging the LTE-Advanced carrier aggregation feature; and validation of protocols for multiple access, synchronization and spectrum coexistence.

Millimeter wave (mmW) bands between 30 and 300 GHz offer two orders of magnitude more spectrum than what is currently allocated for mobile cellular networks [15]. Consequently, they have become a key focus of the research towards 5G especially from a small cell perspective. The very different propagation characteristics of the mmW bands mean that making use of beamforming is crucial with the associated issues of synchronization and broadcast transmissions. The OAI platform can be extended with a suitable RF front-end to facilitate study of beamforming techniques, multiple access and relaying mechanisms for mmW bands.

3.5 Software Defined Mobile Networks

Software defined networking (SDN) is bringing about a paradigm shift in networking through the ideas of programmable network infrastructure and decoupling of network control and data planes. It promises simplified network management and easier introduction of new services or changes into the network. Use of SDN concepts in 4G/5G mobile cellular networks is also being seen to be beneficial (e.g., for more effective radio resource allocation through centralization, seamless mobility across diverse technologies through a common control plane) [16].

The open software implementation of full LTE system in OAI makes it easier to add SDN capabilities to any part of the mobile network and study relevant research issues. For example, the OAI can be used to assess the benefit of SDN based fine-grained resource control based on traffic types (e.g., machine-type vs. human-type). Other examples include experimentation with software-defined radio access networks [17] and virtualization of RAN from the core network perspective [18].

4. CONCLUSION

We have presented the OpenAirInterface as a suitably flexible platform for 5G research that offers (i) an open-source reference software implementation of 3GPP-compliant LTE/LTE-A systems for real-time indoor/outdoor experimentation and demonstration, and (ii) a built-in emulation capability that provides repeatable and scalable experimentation in the controlled laboratory environment on the real execution environment while respecting the frame timing constraint.

We highlighted the use of OAI in the context of 5G research directions, and believe that OAI has the potential to become a reference evaluation platform for 5G technology development by providing researchers with a rapid prototyping and testing environment with which new innovations can be achieved through experimentation.

Acknowledgements

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5. REFERENCES

[1] F. Boccardi et al. Five Disruptive Technology Directions for 5G. *IEEE Communications*, 52(2):74–80, Feb 2014.

[2] I. Chih-Lin et al. Toward Green and Soft: A 5G Perspective. *IEEE Communications*, 52(2):66–73, Feb 2014.

[3] N. Bhushan et al. Network Densification: The Dominant Theme for Wireless Evolution into 5G. *IEEE Communications*, 52(2):82–89, Feb 2014.

[4] W. Chin, Z. Fan, and R. Haines. Emerging Technologies and Research Challenges for 5G Wireless Networks. *IEEE Wireless Communications*, 21(2):106–112, Apr 2014.

[5] The OpenAirInterface Initiative. http://www.openairinterface.org/.

[6] K. Tan et al. Sora: High-Performance Software Radio Using General-Purpose Multi-Core Processors. *Communications of the ACM*, 54(1):99–107, Jan 2011.

[7] Amarisoft. http://www.amarisoft.com/.

[8] nwEPC - EPC SAE Gateway. http://sourceforge.net/projects/nwepc/.

[9] L. Chen et al. System-Level Simulation Methodology and Platform for Mobile Cellular Systems. *IEEE Communications*, 49(7):148–155, Jul 2011.

[10] J. C. Ikuno, M. Wrulich, and M. Rupp. System Level Simulation of LTE Networks. In *Proc. 71st IEEE Vehicular Technology Conference (VTC 2010-Spring)*, 2010.

[11] G. Piro et al. Simulating LTE Cellular Systems: An Open-Source Framework. *IEEE Transactions on Vehicular Technology*, 60(2):498–513, Feb 2011.

[12] K. Amiri et al. WARP, a Unified Wireless Network Testbed for Education and Research. In *Proceedings of IEEE MSE*, 2007.

[13] S. Bhaumik et al. CloudIQ: A Framework for Processing Base Stations in a Data Center. In *Proc. ACM MobiCom*, 2012.

[14] M. Buddhikot. Towards a Virtual Cellular Network with Variable Grade Spectrum: Challenges and Opportunities. In *Proc. ACM MobiCom*, 2013.

[15] S. Rangan, T. Rappaport, and E. Erkip. Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges. *Proceedings of the IEEE*, 102(3), 2014.

[16] L. Li, Z. M. Mao, and J. Rexford. Towards Software-Defined Cellular Networks. In *Proc. European Workshop on Software-Defined Networks (EWSDN)*, 2012.

[17] A. Gudipati, D. Perry, L. Li, and S. Katti. SoftRAN: Software Defined Radio Access Network. In *Proc. ACM SIGCOMM Workshop on Hot Topics in Software Defined Networking (HotSDN)*, 2013.

[18] A. Dawson, M. K. Marina, and F. J. Garcia. On the Benefits of RAN Virtualization in C-RAN Based Mobile Networks. In *Proc. European Workshop on Software-Defined Networks (EWSDN)*, 2014.