MONROE-SOPHIA - A Software Radio Platform for Mobile Network Measurement

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***Abstract*—SOPHIA is the software radio extension to the MONROE measurement and experimentation project. Under MONROE, fixed and mobile nodes for network measurement and experimentation have been distributed across 4 European countries. Each node provides a powerful platform for wireless systems analysis, consisting of a flexible PC and a number of mobile broadband modems connected to different operator networks. Through the SOPHIA project extension, MONROE nodes have been enhanced with software radio capabilities, greatly expanding the range of measurements and experiments which can be supported by the platform. This paper presents the SOPHIA project extension, describing the baseband and RF front-end hardware selected to enhance the MONROE nodes and outlining the software tools which can be leveraged by the new, enhanced platform. The capabilities of the SOPHIA-enhanced MONROE platform are illustrated using detailed performance measurements of LTE networks, obtained during Mobile World Congress 2017 in Barcelona, Spain.**

***Index Terms*—Software Radio, Mobile Network Measurement, LTE, 4G.**

I. Introduction

MONROE is a project to build dedicated infrastructure for measuring and experimenting in mobile broadband (MBB) and WiFi networks under the EU Horizon 2020 research and innovation programme [1]. This dedicated infrastructure comprises fixed and mobile nodes distributed across Norway, Sweden, Spain and Italy. Each MONROE node includes a robust single-board computer equipped with modems to connect to up to three MBB providers and WiFi where available. Nodes are flexible and powerful enough to run a wide range of measurement and experiment tasks including performance and reliability measurements of MBB networks, experimentation with novel services and applications and experiments which exploit the availability of multiple simultaneous broadband links. Measurement results and metadata such as cell IDs, signal strength and connection type obtained from externally connected modems are provided as open data for public use.

SOPHIA is a project extension which enhances the MONROE nodes with software radio capabilities. A software radio is a radio system where components such as modulators/demodulators, filters, detectors etc. which have historically been implemented in hardware, are instead implemented in software upon a general-purpose processing platform. Using software radio, a single hardware platform comprising a radio and processor can be used to implement a huge range of applications, from scanners and spectrum analyzers to complete basestations and terminals.

The addition of software radio capabilities to the MONROE testbed vastly enhances the detail with which mobile broadband networks can be measured and analyzed. Software radio offers the ability to scan, measure and analyze across all frequency bands currently used for mobile broadband in Europe. A single hardware platform can be used to analyze any wireless network, simply by choosing the software application to perform that analysis. By updating these software applications over the air, the platform can be enhanced to perform new measurements, to include new network features in its analysis or to target completely new wireless networks. Such over the air updates could be used for example to add support for the new NB-IoT waveforms of LTE Release 13 to existing measurement tools.

This paper provides an overview of the MONROE-SOPHIA project extension, introducing the hardware and software elements involved and presenting some initial LTE measurement results obtained during the 2017 Mobile World Congress in Barcelona, Spain. Section II outlines the MONROE-SOPHIA platform and discusses some key choices involved in its design before describing the software tools which can be leveraged by the platform. Section III presents our measurement results from MWC17 and Section IV concludes the paper.

II. The MONROE-SOPHIA Platform

MONROE measurement and experimentation nodes consist of a PC Engines apu1d4 single-board PC based on an AMD 1GHz dual core processor. This PC is coupled with 3 ZTE MF910 MiFi devices with LTE modems, miniPCI Wifi card and miniPCI LTE card for management. When deployed, each of the three MF910 devices connects with a separate operator network to support measurement and experimentation. The miniPCI LTE card connects with a single operator and provides a reliable control and management connection to the node. An assembled node for stationary deployment can be seen in Figure 1 below.

To add software radio capabilities to the MONROE node, two main components are required; a baseband processor and an RF front-end. The RF front-end provides the ability to send and receive raw radio signals. It can be tuned to a particular carrier frequency and can transmit or capture signals using a specified sample rate and bandwidth. These raw

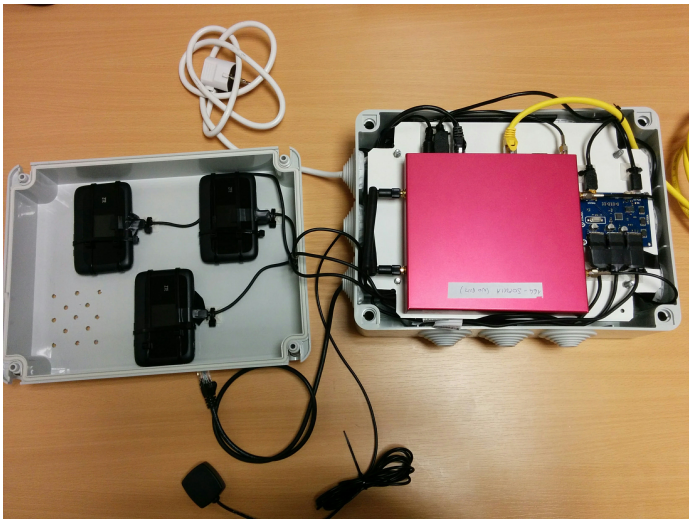

Fig. 1: MONROE measurement and experimentation node.

Fig. 2: The Odroid XU4 baseband processor.

signals are transferred in baseband IQ format to and from the baseband processor. The role of the baseband processor is to generate raw radio signals for transmission and to process and demodulate raw received signals. In the context of measuring mobile broadband networks, the RF front-end can capture the raw signal data for an active mobile operator network and the baseband processor can analyze it by performing synchronization, equalization and demodulation.

For the SOPHIA extension, it was decided to use a dedicated software radio baseband processor rather than attempt to reuse the existing apu1d4 PC. This approach offers more flexibility for the overall MONROE platform while isolating the compute intensive signal processing tasks of the software radio applications from the other MONROE applications and experiments. Two candidate processors were considered - the Odroid XU4 and the Commell LP-173. The XU4 features a Samsung Exynos5422 ARM processor with 4 Cortex A15

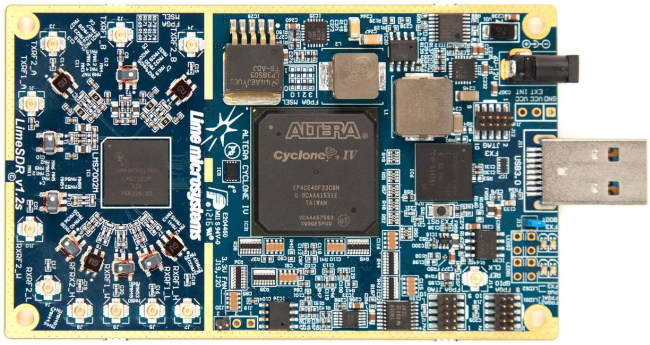

Fig. 3: The LimeSDR RF front-end.

cores (max 2.1GHz) and 4 Cortex A7 cores (max 1.5GHz). The LP-173 on the other hand is a picoITX board featuring an Intel Atom E3845 processor with 4 cores (max 1.91GHz). Following tests with each board, the Odroid XU4 was selected for its greater ease of use, operating system support, higher performance and lower cost. The XU4 board can be seen in Figure 2.

Three candidate RF front-end boards were considered for SOPHIA - the Ettus Research B200mini [2], the Nuand bladeRF x40 [3] and the Lime Microsystems LimeSDR [4]. The B200mini supports a frequency range of 70MHz - 6GHz and an instantaneous bandwidth of 30.72MHz. Single transmit (tx) and receive (rx) channels are supported in full duplex mode. The bladeRF x40 supports a frequency range of 300MHz - 3.8GHz and an instantaneous bandwidth of 28MHz. Like the B200mini, the bladeRF supports single tx and rx channels in full duplex mode. The LimeSDR is the only board which supports two tx and rx channels in full duplex mode, supporting a frequency range of 100KHz - 3.8GHz and an instantaneous bandwidth of 30.72MHz.

To choose the preferred RF front-end for SOPHIA, a suite of tests were carried out with each candidate board. These tests focused on the ability of each to support the streaming data rates required to analyze live LTE 4G networks when used with the Odroid XU4 baseband processor. Test results showed that both the bladeRF and LimeSDR boards are capable of supporting the higher sampling rates required to analyze 20MHz LTE carriers. When used with the XU4, the B200mini supports carriers up to 15MHz but cannot sustain the rates required for a 20MHz carrier. Following our tests, the LimeSDR front-end was selected for its higher performance, dual-channel support and lower cost. The LimeSDR board can be seen in Figure 3.

Of equal importance to the hardware selected for SOPHIA are the software applications available for measurement and experimentation on the platform. A key benefit of the SOPHIA software radio extension is the huge range of existing open-source software radio projects which can be leveraged. Large developer and user communities already exist around projects such as srsLTE [5], openLTE [6], openBTS [7], GnuRadio [8]

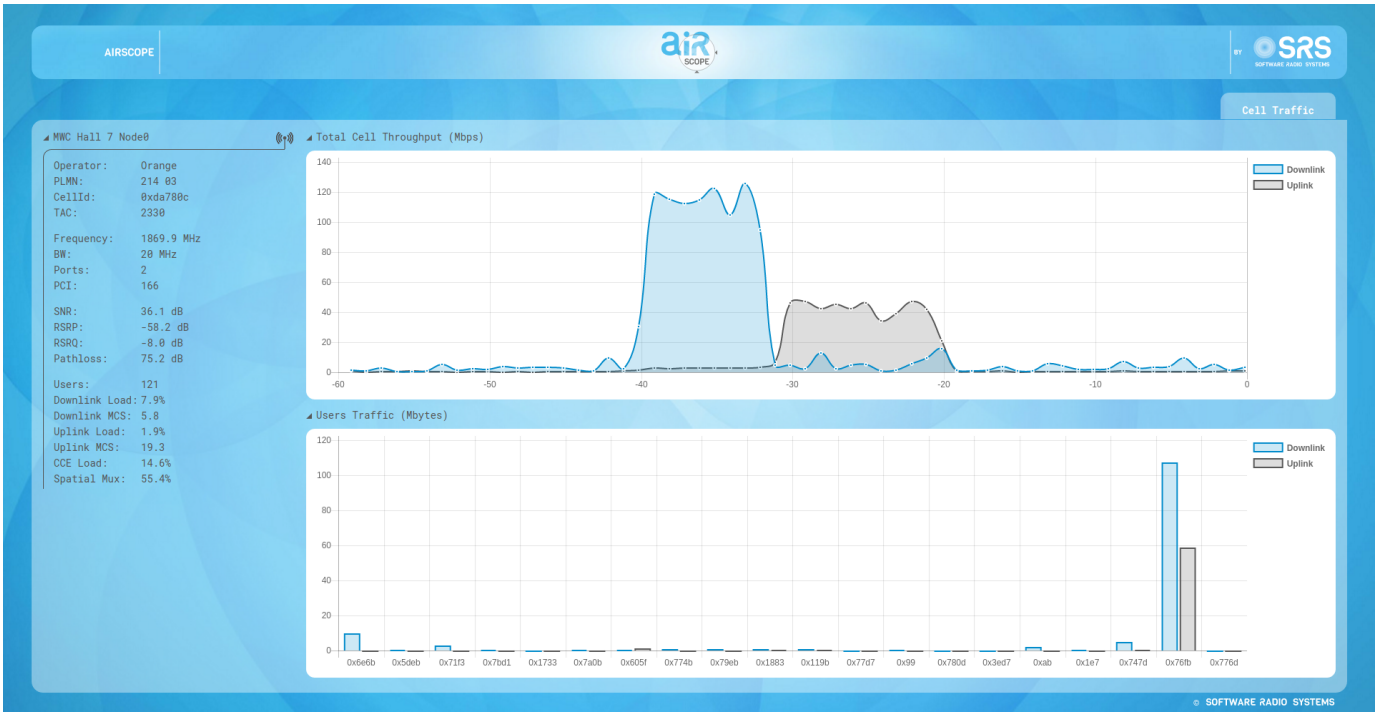

Fig. 4: AirScope capture for Orange cell in band 3.

and OpenAirInterface [9]. The SOPHIA-enhanced MONROE platform offers a compelling testbed for research and experimentation for this community.

The srsLTE project [10] is a suite of open-source libraries and applications for the 3GPP LTE standard developed and maintained by Software Radio Systems (SRS). At the core of the software suite is the srsLTE DSP library which forms the basis of a number of applications including srsUE [11], a complete LTE UE implementation in software radio supporting all layers of the network stack from PHY to IP. In addition to srsUE, the srsLTE suite includes a range of tools for measurement and analysis of 4G LTE networks such as the *cell_search* and *cell_measurement* examples which support scanning, signal detection and measurements of live signal parameters including RSRP, RSRQ, SINR and RSSI. They further support the reception and decoding of LTE System Information Blocks, providing extensive information about the LTE network configuration.

In addition to the wide range of open-source libraries and applications which can be leveraged by the SOPHIA extension are a number of commercial software solutions for mobile broadband network measurement. One such commercial application is AirScope [12], a high-performance LTE air interface analyzer provided by SRS and deployed across the MONROE nodes as part of the SOPHIA project extension. AirScope is a turnkey solution which provides the ability to passively observe, capture and analyze all activity in an LTE cell. The application works by detecting all active users in a given cell and decoding the control information broadcast by the network to those users. These control channel (PDCCH) messages include a huge amount of information including the data throughput in downlink and uplink on a per-user and cell-wide basis, the per-user channel quality, the distance of each user from the cell tower, the cell spectral efficiency, the eNodeB scheduler performance and the use of multi-antenna transmissions in addition to all System Information Blocks (SIBs), paging messages, HARQ indicators etc. Measurement results presented in the next section were obtained using AirScope.

III. Measurement Results

The Mobile World Congress is the biggest mobile event in the world, drawing 108,000 attendees to the Fira Gran Via exhibition centre in Barcelona in February 2017. Each year, high-level mobile network performance at the event is monitored by Ookla, a well-known internet speed-testing service. Overall performance results for the week showed significant improvements over last year [13], along with considerable differences in throughput performance between the main operators.

While the Ookla results provide a high-level view of performance comparisons between operators, we are interested in the key factors underlying these high-level metrics. To gain a deeper insight into these underlying factors, we used AirScope, the SRS LTE air interface analyzer. AirScope provides real-time over-the-air decoding capabilities for network analysis, giving a deep insight into all of the factors behind the headline performance figures. We deployed a node running AirScope in Hall 7 of the exhibition centre and monitored the performance of a number of operators throughout the week of the event.

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====== Downlink =========

--Signal--------------------------UEs---CCE---------DL--------------------------------UL----------------------
  rsrp  rsrq    pl   snr    proc   act   total used   bps   mcs    prb    time   mimo   bps   mcs   prb    time
   -56   -15    73    25   100%   113    17    16%   118M    24    93%    87%    90%   2.8M    21    18%    32%
   -56   -15    73    24   100%   115    18    16%   115M    24    93%    86%    90%   2.4M    20    16%    31%
   -57   -16    75    25   100%   115    17    18%   112M    23    91%    84%    88%   2.9M    13    13%    47%
   -56   -14    73    25   100%   112    18    22%   115M    22    90%    89%    87%   2.9M    11    10%    65%
   -56   -14    73    24   100%   112    17    21%   122M    24    94%    89%    91%   3.1M    11    11%    67%
   -58   -14    75    24   100%   114    17    20%   126M    23    94%    93%    90%   3.1M    20    14%    45%


====== Uplink =========


--Signal--------------------------UEs---CCE---------DL--------------------------------UL----------------------
  rsrp  rsrq    pl   snr    proc   act   total used   bps   mcs    prb    time   mimo   bps   mcs   prb    time
   -57  -9.8    74    37    99%   126    18    24%   2.5M   3.6    17%    78%    87%    47M    23    89%    99%
   -57  -9.2    74    37    99%   126    18    21%    13M   8.9    24%    76%    89%    42M    23    87%    91%
   -57  -9.6    74    36    99%   123    18    22%   2.6M   5.7    17%    68%    87%    45M    23    89%    96%
   -56   -11    73    36    99%   122    17    20%   5.0M   6.2    17%    70%    90%    42M    23    88%    91%
   -57  -9.8    74    37    99%   126    18    23%   5.0M   5.7    19%    74%    87%    46M    23    88%    99%
   -57   -11    74    38    99%   118    17    20%   5.7M   5.2    20%    81%    91%    47M    24    90%    99%
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Fig. 5: AirScope detailed statistics for Orange cell.

Collected statistics were pushed to our cloud-based display at [14].

To obtain an in-depth analysis of the behaviour of each operators network, we configured our node to analyze the local cell. We then used a test handset (a Nexus 5 with Qualcomm Snapdragon 800 running Android 6.0.1) to carry out a speed test on that cell. Using this approach, we examined the local cell for operators Orange and Vodafone.

A. Orange

The local Orange cell was deployed in LTE band 3 at 1870 MHz. The cell was configured for 100 PRBs, using a bandwidth of 20MHz. The AirScope screen capture illustrated in Figure 4 provides the high-level statistics for the cell, along with the captured traffic details during the execution of our speed test. From the capture, we can see that the signal level was exceptionally good with SNR estimated at 36.1dB. This would indicate the use of a small-cell device within Hall 7. In the upper chart, the total cell throughput in downlink and uplink is illustrated over a period of 60 seconds. Our speed test can clearly be seen, reaching downlink speeds of 120Mbps and uplink speeds of 45Mbps. In the lower chart, uplink and downlink traffic for the most active 20 users on the cell is presented. Our test handset can clearly be seen with Radio Network Temporary Identifier (RNTI) 0x76fb. It is interesting to note that, aside from our speed test traffic, overall cell traffic levels are relatively low.

The AirScope graphical interface provides high-level information about the cell and the observed traffic. However, to get a deep insight into the cell performance, we can look at the detailed statistics provided by the AirScope console trace. In Figure 5, we present snippets from this trace. On the top, we can see the statistics for the cell while our downlink speed test was running. On the bottom, we can see the same statistics gathered while our uplink test was running.

The acronyms used for each column are as follows:

Signal

- RSRP: Received Signal Reference Power
- RSRQ: Received Signal Reference Quality
- PL: Pathloss
- SNR: Signal-to-Noise Ratio
- PROC: Percentage of total signal successfully processed by AirScope

UEs

- act: Number of active UEs on the cell

CCEs

- total: Total number of Control Channel Elements
- used: Used number of Control Channel Elements

DL

- bps: Bits Per Second
- mcs: Modulation and Coding Scheme
- prb: Percentage of Physical Resource Blocks Used (Frequency Occupancy)
- time: Percentage of Time Symbols Used (Time Occupancy)
- mimo: Percentage of Resource Blocks Using MIMO

UL

- bps: Bits Per Second
- mcs: Modulation and Coding Scheme
- prb: Percentage of Physical Resource Blocks Used (Frequency Occupancy)
- time: Percentage of Time Symbols Used (Time Occupancy)

From our detailed AirScope statistics, we can easily see the key factors behind the high speed test performance. Looking first at the downlink, we can see that the SNR is very high at 24-25 and this permits the use of an efficient DL MCS (22-24). Also, the scheduler in the Orange eNB makes good use of

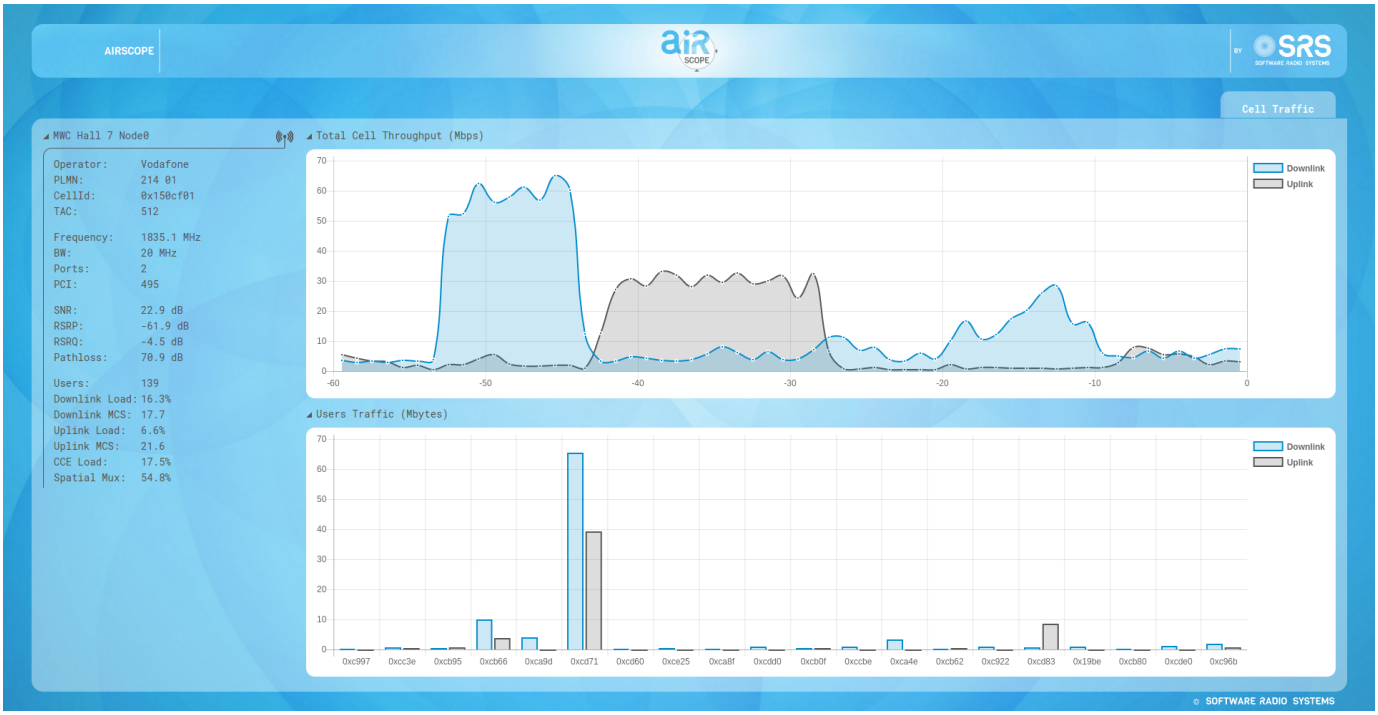

Fig. 6: AirScope capture for Vodafone cell in band 3.

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====== Downlink =========

--Signal-------------------------UEs---CCE---------DL--------------------------------UL----------------------
  rsrp  rsrq    pl   snr    proc   act   total used   bps    mcs    prb    time   mimo    bps    mcs    prb    time
   -60  -9.6    69    26    80%    96    24    26%   46M     19    95%    94%    15%   1.5M    21    14%    24%
   -60  -9.2    69    26    80%    92    22    29%   46M     20    96%    92%    15%   2.0M    21    18%    25%
   -60  -9.7    69    23    80%    90    26    27%   48M     20    95%    94%    15%   3.0M    21    24%    27%
   -61  -9.5    70    17    80%    85    25    31%   50M     20    96%    96%    14%   2.9M    21    22%    28%
   -61  -9.5    70    23    80%    78    27    28%   50M     20    94%    97%    18%   3.3M    22    22%    33%
   -60  -9.5    69    25    80%    76    29    27%   50M     20    96%    97%    18%   2.4M    21    18%    30%

====== Uplink =========

--Signal-------------------------UEs---CCE---------DL--------------------------------UL----------------------
  rsrp  rsrq    pl   snr    proc   act   total used   bps    mcs    prb    time   mimo    bps    mcs    prb    time
   -60  -5.4    69    28    80%    65    55    14%   4.0M    16    23%    80%    28%    33M    23    83%    79%
   -62  -4.9    71    26    80%    62    43    18%   4.7M    16    19%    80%    39%    31M    22    82%    77%
   -61  -5.4    70    29    80%    60    37    19%   4.4M    16    19%    75%    51%    32M    23    80%    78%
   -61  -4.2    70    29    80%    60    32    20%   6.2M    17    22%    74%    44%    30M    23    82%    73%
   -61  -5.2    70    25    80%    59    41    17%   4.9M    15    27%    69%    36%    28M    23    80%    68%
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Fig. 7: AirScope detailed statistics for Vodafone cell.

the resources both in frequency (90-94%) and time (84-93%). However, arguably the most important factor is the aggressive use of MIMO, as indicated by the percentage of resource blocks where 2x2 MIMO was used (88-91%). Looking at the uplink results, we can see that high UL MCS (23-24) and good use of time and frequency resources result in high speeds. However, as MIMO is not available in the uplink, overall speeds are lower than those of the downlink. Finally, we can see that apart from the traffic generated by our speed test, the cell is relatively uncongested.

B. *Vodafone*

Having examined the performance of the local Orange LTE cell, we then took a look at the local Vodafone cell. From our AirScope screen capture in Figure 6, we can see that this cell was also deployed in Band 3, at 1835 MHz. As with the Orange cell, the Vodafone cell also uses 100 PRBs for a bandwidth of 20MHz. Again, we can see that the signal level was good with SNR estimated at 22dB. As with the Orange cell, this would indicate the use of a small-cell device within Hall 7.

Our speed test traffic can be clearly seen in the top chart,

first the downlink test reaching speeds of up to 60Mbps and then the uplink test reaching speeds of up to 35Mbps. In the lower chart we can see our handset with RNTI 0xcd71. Apart from the traffic generated by our test, we can see a number of other users are also active on the cell.

Looking at the more detailed statistics from the AirScope console trace in Figure 7, we can see why the Vodafone cell achieves lower speeds than the Orange cell. Looking first at the downlink results, we can quickly identify the biggest differentiators between the cells. While the Orange cell uses MIMO aggressively, the eNodeB scheduler in the Vodafone cell only uses MIMO in 14-18% of the resource blocks used. Also, while the Orange cell uses MCS values of 22-24, the Vodafone cell manages downlink MCS values of 19-20. A further factor resulting in lower downlink speeds is the use of more Control Channel Elements by the Vodafone cell, leaving fewer resources for data transmission. In the uplink, the lower Vodafone speeds can be explained by the lower MCS values used (22-23 vs 23-24) and the lower time and frequency resource usage.

These measurement results illustrate the insights which can be obtained using a flexible, powerful, software-radio tool for mobile broadband network analysis. The high-level measurements obtained using an application-layer speed-test tool like Ookla provide basic performance comparisons between different operator networks. However, a software-radio based analysis tool can be used to dig into the key factors underlying those performance comparisons and to gain a deeper understanding of mobile broadband network behaviour.

IV. Conclusions

This paper has presented SOPHIA, the software radio extension to the MONROE measurement and experimentation platform. Under SOPHIA, the MONROE node design has been enhanced with a powerful baseband processing unit and flexible RF front-end to support a wide range of high-performance software radio applications. The addition of software radio capabilities to the MONROE testbed through SOPHIA promises to significantly expand the range of experiments which can be supported, to enhance the value of existing experiments and to greatly increase the pool of potential testbed users and experimenters. To illustrate the benefits of software radio for a platform like MONROE, we have presented a set of detailed LTE network performance measurements, obtained during Mobile World Congress 2017 using the commercial AirScope LTE air interface analyzer. These measurements clearly show how a software radio platform can be used to gain deep insights into the factors underlying mobile broadband network performance.

Acknowledgments

This project has received funding from the European Unions Horizon 2020 research and innovation programme under grant agreement No 644399.

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