Dynamic and Collaborative Spectrum Sharing: The SCATTER Approach

Spilios Giannoulis*, Carlos Donato‡, Ruben Mennes‡, Felipe A. P. de Figueiredo*, Irfan Jabandžić*, Yorick De Bock‡
Miguel Camelo‡, Jakob Struye‡, Prasanthi Maddala†, Michael Mehari*, Adnan Shahid*, Dragoslav Stojadinovic†
Maxim Claeys‡, Farouk Mahfoudhi‡, Wei Liu*, Ivan Seskar †, Steven Latre‡, and Ingrid Moerman*
*imec - IDLab, Department of Information Technology at Ghent University, Ghent, Belgium.
†WINLAB, Rutgers University, New Brunswick, NJ, USA.
‡Department of Computer Science, University of Antwerp - imec, Antwerp, Belgium.
Email: *[fistname.lastname]@ugent.be, †[prasanti,stojadin,seskar]@winlab.rutgers.edu, ‡[fistname.lastname]@uantwerpen.be

***Abstract*—This paper presents the architecture and the basic principles behind the design and implementation of the SCATTER system, a wireless end-to-end communication system that participated in the DARPA Second Spectrum Collaboration Challenge (SC2). The focus is mainly on presenting the architecture and the supported interactions between the different components of the system in order to deliver a true dynamic collaborative spectrum allocation and usage, while coexisting with numerous unknown heterogeneous wireless technologies.**

***Index Terms*—dynamic spectrum allocation, collaboration, system architecture, AI/ML, differentiated QoS**

I. Introduction

The traffic demand on wireless technologies is increasing more and more over the years [1] and the explosive emergence of new standards, covering licensed and unlicensed spectrum bands has triggered the appearance of tens of standards of wireless technologies, with many of them competing for the same spectrum band instead of harmoniously sharing it [2]. Unfortunately, the wireless spectrum is a scarce resource, and the available frequency bands will not scale with the foreseen demand for new capacity [3]. Certain parts of the spectrum, in particular the license free ISM bands, are overcrowded, while other parts, mostly licensed bands, may be significantly underutilized. As such, there is a need to introduce more advanced techniques to access and share the wireless medium, either to improve the coordination within a given band, or to explore the possibilities of intelligently using unused spectrum in underutilized (e.g., licensed) bands.

Numerous efforts have already taken place in order to enable coexistence and/or cooperation between resident technologies, especially focusing on the ISM bands. Most of these efforts focus on delivering techniques for coexistence based on the inherent characteristics of specific technologies like Wi-Fi, Bluetooth and ZigBee that reside in the ISM bands as well as LTE-LAA, LTE-U and Multifire that also aspire to enter the ISM bands [4] . None of those techniques is generic enough to be generalized, even worse, most of them are simple sense-and-avoid techniques [5] or even fixed duty cycle based that proclaim some technology as the main user of the spectrum band while the rest compete for the empty leftover parts. The Second Spectrum Collaboration Challenge aims to deliver a new way of dynamically sharing the spectrum without the need for technology specific knowledge, providing a framework of cooperative sharing of the spectrum, while offering fairness and true coexistence in any possible spectrum range, aspiring to brake even the barriers between free and licensed bands. With the recent launch of CBRS in the USA, the dynamic spectrum sharing era has just started [6].

We would like to thank DARPA SC2 for partially funding our team through prizes.

II. SCATTER System Level Architecture

A. General Architecture

SCATTER system has been designed to split every functionality within different modules, all connected through a common data bus where all information is exchanged. Figure 1 shows the general architecture of our software design and summarizes the interaction across modules. The main purpose of this approach is i) to provide an abstraction layer that allows developers to code modules using different programming languages, choosing the most convenient one depending on the feature: while most of the modules are written in C/C++, the ML modules are written in python using third party frameworks such as TensorFlow[1] and CuPy [2] to offload matrix computations to the GPU; ii) to offer a fail-safe system: as each module is an individual system process, in case that one of them crashes, SCATTER system can just restart that process during runtime; and iii) to follow a plug-in approach: replacing, deleting or adding a certain functionality, is just a matter of attaching another process to the data bus. Therefore, the API for any information exchange or supported functionality is defined as a message template that two or more modules can exchange.

As shown in Figure 1, SCATTER has three main blocks: the data and control plane, as well as an RF Monitor (RF-Mon) module. The Data plane is composed by the User Data Management (UDM), MAC and PHY modules. The

[1]https://www.tensorflow.org
[2]https://cupy.chainer.org

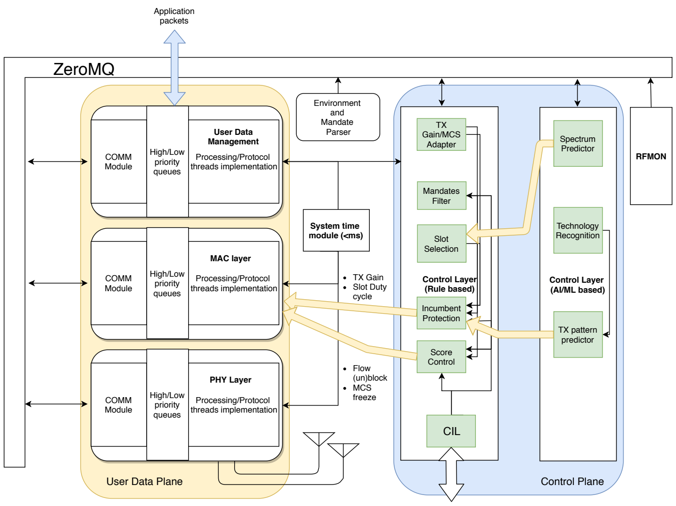

Figure 1: SCATTER system architecture.

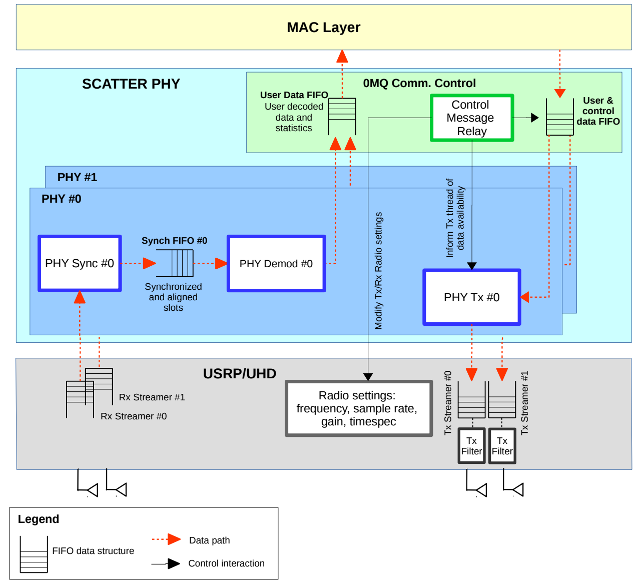

Figure 2: High-level architecture of the SCATTER PHY.

Control plane is composed by two main modules: the rule-based and the AI/ML-based Control Layers. The RFMON module offers real time spectrum monitoring in the form of a continuous stream of FFT samples. A system time module provides synchronization to all modules based on system clock. Finally, some additional blocks are included to support specific requirements in the context of the SC2 challenge: the Collaborative Intelligent Radio Networks (CIRN) Interaction Language (CIL) module, used to interact with other networks, and the environment and traffic flows QoS parser (we shall call a flow with specific QoS requirements a mandate from now on), responsible to accept input on required settings of the RF front-end and data traffic types along with their QoS characteristics.

B. Layers description

1) SCATTER PHY description: The high-level architecture of the SCATTER PHY is depicted in Figure 2. The figure illustrates the different software/hardware layers composing the SCATTER PHY and the threads within each one of them. Red dashed arrows indicate data paths while black arrows indicate control/information interaction between threads.

The SCATTER PHY is implemented as a software defined radio (SDR) and is built upon the srsLTE library [11], evolving beyond the existing LTE features. It communicates to a Universal Software Radio Peripheral (USRP) X family of SDR devices including NI's RIO platforms[3] [8] for passband conversion and transmission using the USRP Hardware Driver (UHD) software API [9, 10]. As can be seen in the figure, the individual PHY modules are connected to the ZeroMQ (Data/Control) module, also known as 0MQ, which interconnects the SCATTER PHY with the MAC layer through the ZeroMQ bus [7]. This module manages the exchange of control and statistics messages between the SCATTER PHY and MAC layer.

Communication with the SCATTER PHY is implemented through a well-defined interface designed with Google's Protocol Buffers (protobuf)[4] for data serialization coupled with the ZeroMQ messaging library [7] for distributed exchange of control, statistics and data messages. Implementing the ZeroMQ push-pull pattern allows local or remote MAC layer's real-time configuration of several parameters and reading of several pieces of information/statistics provided by the SCATTER PHY. Based on the ZeroMQ logic, PHY and MAC layers are able to exchange control and data messages following a non-blocking communication paradigm. The SCATTER PHY was designed to be completely decoupled and independent of the MAC layer module, not posing any constraints on hardware, software and/or programming language adopted by it. The SCATTER PHY contains the following set of main features:

- OFDM waveform: We adopt Orthogonal Frequency-Division Multiplexing (OFDM) as the SCATTER PHY waveform. OFDM is a mature technology, which is implemented in a wide range of products due to its several advantages such as robustness to severe multi-path fading, low implementation complexity, easy integration with MIMO, simple channel estimation, etc. [14].
- Bursty transmissions: with discontinuous transmissions it is possible to improve the use of available spectrum and to coordinate its usage with other networks/radios in an opportunistic/intelligent/collaborative way.
- Dual-Concurrent PHYs: having two physical interfaces simultaneously transmitting and receiving at independent frequencies enables Multi-Concurrent-Frequency Time-Division Multiple Access (McF-TDMA) scheme to be implemented by the MAC layer. The ability to allocate concurrent slots allows for more flexible spectrum utilization, as vacant disjoint frequency chunks can be concurrently used.
- FPGA-based filtered transmissions: filtering the transmit-

[3]https://www.ettus.com/product/category/USRP-X-Series

[4]http://code.google.com/p/protobuf/

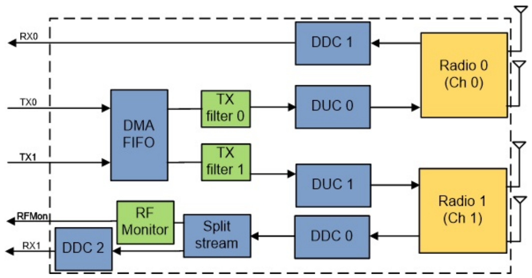

Figure 3: FPGA configuration with dual PHY and RFMON

ted signal effectively minimizes out-of-band emissions (OOBE), allowing better spectrum utilization by enabling radios to have their transmissions closer to each other in the frequency domain.

- Out-of-Band Full-Duplex operation: both PHYs operate completely independently, meaning that Tx and Rx modules are able to transmit and receive at different channels, set different gains and use different PHY BWs.
- Timed-commands: this feature allows the configuration of the exact time in the future to (i) start a transmission and (ii) change Tx/Rx frequencies/gains.

2) RFMON description: The RFMON module is very important to the whole system as it gives the CL layer a local insight of the spectrum usage, by enabling CL to access spectrum sensing measurements. These measurements are used to train machine learning algorithms employed to better understand the environment, optimize the spectrum usage and cooperatively work with other networks, completely agnostic to other network's characteristics. RFMON continuously monitors the whole competition bandwidth which can go up to 40MHz in an SC2 scenario. Performing this compute-intensive task on the FPGA, reduces CPU load. It also reduces the amount of data to be transferred from USRP to host, as only periodic snapshots (time averaged spectral energy) are sent to the host. This custom FPGA module along with transmit FIR filters, was built and integrated within the SCATTER system using Ettus Research RFNoC framework as shown in Fig. 3. As SCATTER uses dual-concurrent PHY, samples from the second radio are split into 2 streams, with one stream feeding RFMON and the other stream feeding RX1 decoding pipeline.

3) MAC description: The SCATTER MAC protocol is based on an enhanced MF-TDMA scheme, taking advantage of our dual concurrent PHY support and the separated RX and TX channels offered per PHY. Since 2 slots can be active at the same time using PHY0 and PHY1, we can support a McF-TDMA table where 2 slots can be allocated for TX and 2 slots for RX at any given timeslot per node. By employing a McF-TDMA scheme, our CIRN can utilize the entire offered spectrum if needed. MAC layer maintains a McF-TDMA table per node and updates it with every successful slot allocation/removal procedure. Example of a McF-TDMA table is shown in Figure 4.

MAC layer is also responsible for exchanging slot allocation/removal control messages and for notifying neighbor nodes about any newly allocated/released time-frequency slots

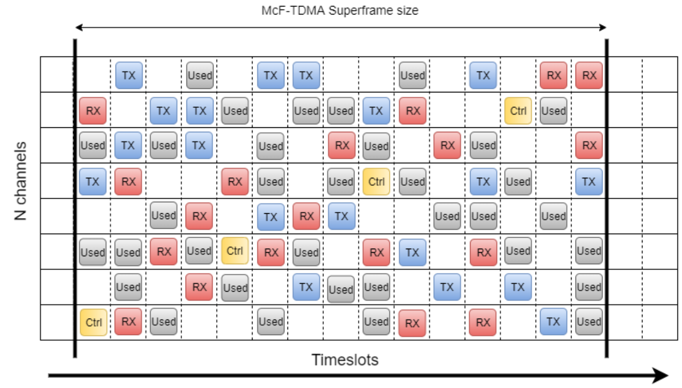

Figure 4: McF-TDMA slot table structure and possible states.

(patent pending). Based on the latency and throughput requirements of an incoming flow, MAC layer initiates one/multiple slot allocation procedures towards the destination node in order to serve the incoming traffic. As a protection mechanism against failures in slot allocation/removal procedures, MAC layer periodically broadcasts table status to neighboring nodes, in order to align all McF-TDMA tables.

The MAC protocol is based in 3 generic operations:

- Support of a distributed slot setup protocol with any neighboring node that can perform allocation, deletion and move of any [channelX-timeslotY] slot. Each slot allocated serves traffic of a single link and all flows belonging to it.
- Maintain a schedule MF-TDMA table [slot, channel, type of slot, node] that keeps track of assignment of channel-time slot tuple to transmit (Tx) or receive (RX) to/from a specific node as well as Control-Broadcast (CB) slots.
- Support a semi-static Control-Broadcast slot allocation scheme. CBs are based on slotted aloha medium access if there is a large number of nodes in the network or are divided into mini-slots, where each mini-slot is used by one node, offering a TDMA like medium access. The CB scheme adapts to the channelization of the available bandwidth during boot time to avoid the possibility of CB slots interfering all across the available spectrum.

Apart for the basic MAC operation, several other features exist in the MAC layer to support QoS requirements and link robustness. A double layer of buffering exists to support aggregation/fragmentation of incoming network layer PDUs, in order to fit in the PHY PDU size (based on the running Modulation and Coding Scheme (MCS) on the link) and avoid wasted space. Also re-transmissions are supported based on aggregated acknowledgements sent from the receiver, informing the sender about successfully receiving a packet. Retransmission maximum retries are dynamically calculated per packet to ensure that the latency requirements of every packet will not be violated while data packets are dropped proactively if it is found that it is not possible to be delivered in time to the destination (patent pending).

4) User data management module description: Our decision engine is designed to constantly keep track of the radio performance. To achieve this, UDM reports to CL several metrics per flow such as the amount of packets per second and average packet size. These metrics are crucial for CL to understand how close the node is to fulfill the flow QoS requirements based on reported incoming traffic and therefore, correctly quantify the success of our system. UDM monitors in runtime all incoming traffic flows and reports to several submodules of CL the required monitoring information. UDM also performs buffering when specific bursty types of traffic are injected into our system, taking into account the latency characteristics of the bursty incoming traffic, and reshaping the traffic flow to a CBR like flow.

5) Description of the control layer and decision engine: The Control layer of the SCATTER solution holds the intelligence of the system, making use of all the knobs exposed by the MAC layer in addition to the ground truth vision provided by the RFMon. Those are the main enablers of our decision engine. Any required decision, is taken by the submodules that constitute our decision engine: from MCS and TX gain adaptation, scheduling of the slots, Incumbent Protection (IP) up to traffic prioritization and score control.

a) Individual modules of Control Layer: Here we present the individual modules constituting the CL layer.

- Link adaptation module

In the SCATTER system, link adaptation is controlling two main aspects of a link (e.g. Node A to node B), the MCS and the TX gain used. We kept the RX gain static following the recommendation of NI and the DARPA team to 7 dBm. The link adaptation plays a two-folded role: i) finding optimal settings for initializing and keeping links stable with high Packet Success Rate (PSR) while not interfered, ii) but also to provide the first level of interference countering when other teams' radios would interfere with a specific link. This means that the Link Adaptation algorithm must be able to adapt TX gain and MCS fast enough, when interference is detected through PSR and link statistics like RSSI, CQI. As all data packets are acknowledged from the receiver to the sender, the Acks were used to push also receiver based statistics to the sender, thus closing a fast control loop between the sender and the receiver. This control loop is the core of our link adaptation algorithm.

- Strategy module

We understand collaboration as helping all coexisting communication systems to reach an equal & acceptable level of performance. In the DARPA SC2 context, this translates in helping the ensemble reach the bonus threshold (BT) and protect potential incumbents. Consequently we define two sort of policies that depend on the status of a match: score policies and environmental policies. When the ensemble score is below BT, our score policy sets a target score according to other teams' score from CIL. The target score is calculated based on the second weakest team reported score plus a margin. Since the score of the ensemble may change rapidly, we have defined an aggressiveness factor that modifies the margin of score to grow as fast as the ensemble score does, maximizing our achieved score at the moment the ensemble surpasses the BT. These policies have been implemented following a hybrid approach: the gateway sets the target score while the nodes dynamically choose those mandates that are most beneficial, by employing the mandate prioritization module. As soon as the ensemble crosses the BT, the target score is temporary disabled and our strategy tries to maximize our score by enabling new mandates and wait for them to stabilise into a success state before enabling additional mandates.

On the other hand, a scenario may include incumbents that must be protected. Our strategy module implements two policies that handle passive and active incumbents. In the case of passive incumbents, the policy notifies the TX gain adapter to minimize the transmission power for a given link while prioritizing flows with smaller spectrum footprint. For active incumbent, the policy learns the TX pattern utilizing the information from Technology Recognition (TR) module to dynamically enable/disable the overlapping regions of the superframe. Last but not least, our system is capable to detect jammer presence. The environmental policy limits the upper boundary of the MCS adapter to increase the robustness against interference while the slot predictor helps avoid the regions where the jammer is present.

- Traffic prioritization module

This module is responsible to sort the offered mandates, aiming to maximise the efficiency of our system (spectrum footprint vs achieved score) while also taking into account the related Steady State period. To this end, we have defined a set of benefit-cost functions for each type of mandate to calculate the benefit of a mandate. The most beneficial mandates are selected first to be enabled in order to reach our target score. For every type of mandate, our traffic prioritization module keeps track of its status and evaluates its success. In case that due to bad channel conditions, the system is not able to stabilize a mandate, the node blocks the flow and picks the next most beneficial mandate on the list.

- Slot allocation and spectrum management

The CL selects a slot to be used between two nodes combining the information from multiple input sources. In order to combine these information, the input data must be normalized. To this end, we designed a slot selection system using multiple filters, where each input source is represented as a filter. For each filter output the value is normalized between 0 and 1 as well as the final "Goodness" value of a slot. The slot selection system supports two classes of filters: i) MUL-filters, where the values are multiplied by a factor and then increase the impact of the filter during the slot allocation procedure, e.g. the Incumbent-presence filter downgrades the overlapping slots of the superframe with the incumbent's spectrum region or the External McF-TDMA filter to make sure two nodes do not select the same slot; ii) ADD-filters, with a summation effect to the slot Goodness. Such filters are the Slot prediction filter detailed in Section II-B5b, the Channelizing filter, concentrating slot allocations in one or more frequency channels and Historic voxel filter that uses the voxel information from other teams provided via CIL to lower the Goodness value of parts of the spectrum used by other teams to reach the BT.

During a typical slot allocation procedure between 2 nodes, the TX node, after applying all filters, selects slots with the highest Goodness from available slots and then proposes a subset of these slots to the RX node. The RX node selects then the best slot out of the proposed set based on its own filters, and reports the selected slot back to the TX node.

- Inter-node Reporting/Communication module
Since our strategy module follows a hybrid approach, every node reports the mandate performance metrics and node's spectrum usage to the gateway. The central decision agent employs this information for two main purposes: to calculate the target score and to disseminate these metrics through CIL. In order to reduce control overhead, the size of these messages has been highly optimized. We have also implemented mechanisms to keep the nodes individual states synchronized e.g., the strategy module in the gateway announces the policy to be executed locally in the nodes, the nodes report back to the gateway the current policy running, target score and mandate performance metrics.

- CIL support module
A node acting as gateway is the unique entity of a CIRN that is connected to CIL network. This node is in charge of collecting mandate performance reports and spectrum usage from each node, packing this information in an single report and sending it to other networks. When other networks share any related information, the CIL module parses the messages and passes relevant values to submodules of the decision engine for further processing.

b) ML/AI based modules description: Spectrum sharing is about understanding and predicting the environment in real time. In SCATTER, this is possible using RFMon data providing ground truth vision to the decision engine and allowing spectrum state prediction.

- Slot prediction
Pinpointing and predicting holes in the spectrum is the key and DNA of our system. As detailed in [12], we have designed and implemented a Deep Convolutional Neural Network (CNN) to learn and predict the usage of the spectrum. As a preliminary step, the model was trained offline with spectrum data that was collected in the scrimmages during the second and third phase of SC2. In addition to the knowledge learnt during the offline training, the model is fed with RFMon data for online training during matches to quickly learn, recognize, adapt and predict the (possibly new) behaviour of other networks, aiming to avoid interference with other transmissions. Notice that after each match, the weights of the CNN were stored and used in new matches. Once the CNN have learnt the right features to provide a good performance on most of the scenarios, we keep using the online learning but the resulting weights were not used anymore.. The outcome of the model is a matrix of values with the same shape of our superframe. These values are used as a filter into our slot selection module to enhance the view of our nodes when they select, negotiate, and allocate slots.

- Technology recognition
Identifying what is in the spectrum is key on making better decisions about how to access the spectrum. The TR module uses RFMon data, which is framed according to our superframe size, to discriminate the following five types of radio signals signature: radar, jammer, SCATTER, other teams, noise. It was implemented following the same Deep Neural Network architecture as [13] [15] [16] but modified to support real-time processing with limited computing resources: instead of using raw samples, TR creates spectrograms with no overlapping using the 32-averaged 512-point FFT samples collected by RFMon at 23.04 Msps (or 46.08 Msps if the available bandwidth is > 20 Mhz).

III. Cross layer and data-control plane interactions

In this chapter, the interactions between the main layers and modules of our system are presented, in order to make clear how every layer/module contributes towards achieving true dynamic collaborative spectrum usage.

A. RFMON - Control Layer interactions

RFMON, provides to the CL Layer, a local view of spectrum usage in the competition band. Implemented as an FPGA module, it computes FFT magnitude square of the received samples, and averages a configurable number of these blocks before sending them to the host. These snapshots of spectral energy are sent to the CL Layer over ZMQ as vectors of 32 bit integers using FFT size of 512 and averaging size of 32.

B. PHY - MAC interactions

The communication between the SCATTER PHY and the MAC layer is carried out through the exchange of four predefined messages. The first two, namely, Tx and Rx Control messages, are used to manage subframe transmission and reception respectively. The parameters carried by these two messages can be configured and sent to the individual PHYs by the MAC layer before the transmission of every subframe, hence allowing run-time configuration. The other two messages, namely, Tx and Rx statistics messages, are used to provide real-time feedback from each PHY to the MAC layer, yielding vital information necessary for upper layers to take actions.

C. MAC - CL interactions

MAC layer feeds CL with all data necessary to take optimal decisions. It forwards to CL Tx and Rx statistics received from PHY layer, it extracts statistics incorporated in acknowledgments and sends them to CL as well as slot usage statistics and flow statistics. CL calculates and feeds MAC layer with link level parameters like MCS and TX gain per destination. To increase/decrease or just alter the spectrum signature of the network, it can inform MAC layer to enable/block specific flows or increase/decrease the duty cycle of already allocated slots. MAC layer and CL have also bidirectional interaction in the context of a slot allocation/removal procedure. MAC requests new TX slots based on incoming user data packets, while CL decides which slots are the best slots to allocate. MAC layer also feeds CL with information about slot usage received from other nodes in the network. Since the CL is aware of the current link status and the performance of any traffic flow, it can inform MAC to enable/disable flow specific robustness mechanisms in order to ensure that all flows abide to requested QoS characteristics.

D. User Data Management layer - Control Layer interactions

UDM layer main interaction with the CL is to forward information about the incoming traffic during run-time. These information are packet size per flow, packets/sec per flow and burst detection (size of burst in packets and bytes).

IV. Enhanced features of our Radio

The main overall characteristics that make our system unique to the best of our knowledge so far (as we do not know the internals of the other SC2 systems yet) are as follows:

-Active/passive incumbent protection: Detecting and protecting incumbents is performed via a combination of CIL information and TR. In the case of the active incumbent case, TR provides the time and frequencies where the incumbent is detected in case of low interference, and CIL violation reports is used to enhance this information. The combined information is fed to a pattern recognition and prediction algorithm, in order to learn and predict the time slots and frequencies where the active incumbent will transmit in the near future with respect to our super-frame. For passive incumbent our nodes limit the transmission power jointly with smart traffic prioritization based on spectrum footprint. This way, our system allows others to transmit without crossing the interference threshold of all incumbent variants.

-Spatial reuse of frequency/time slots: SCATTER by design can spatially reuse spectrum, as the slot allocation protocol provides the ability to solve the exposed and hidden node problem, exploiting the full potential of spectrum reuse in a multi-hop environment.

-Decentralised operation: All decisions for dynamic spectrum allocation and usage are taken locally at each node, no need for centralized infrastructure or special node to command and control our system.

-Spectrum usage prediction: Every cognitive radio can detect and react to what is happening in the spectrum today. SCATTER, going beyond the cognitive radio state-of-the-art, can react to past events, but can also predict and react proactively to future spectrum usage events, taking into account patterns and predicting the future usage of the spectrum in run-time when other users are present.

V. Conclusions and Future work

In this work, we have presented a general overview of the SCATTER system, providing a detailed view of the system architecture and the main modules while pinpointing the unique features of our system design and radio capabilities. DARPA SC2 is the first step towards autonomous dynamic spectrum management, proving that collaboration across multiple radio systems is a mechanism that can facilitate co-existance in the same spectrum band. Our solution presents a state-of-the-art system that can solve many of the compelling scenarios where traditional radios are not able to cope with. Our future work will include porting SCATTER outside of the context of the SC2 Colosseum emulator in order to enable experimentation with real wireless environments and assess the performance of our system in real-life scenarios.

Acknowledgment

The project leading to this publication has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 732174 (ORCA project) and from USA NSF under award #1836901 (ICE-T).

References

[1] *Cisco visual networking index: Global mobile data traffic forecast update, 2016-2021*, San Jose, CA, USA, Cisco, White Paper, Mar. 2017.

[2] H. Kour, R. K. Jha, and S. Jain, *A comprehensive survey on spectrum sharing: Architecture, energy efficiency and security issues,* J. Netw. Comput. Appl., vol. 103, no. C, pp. 29-57, 2018.

[3] L. Zhang, M. Xiao, G. Wu, M. Alam, Y.-C. Liang, and S. Li, *A survey of advanced techniques for spectrum sharing in 5g networks,* IEEE Wirel. Comm., vol. 24, no. 5, pp. 44-51, 2017.

[4] V. Maglogiannis, D. Naudts, A. Shahid, S. Giannoulis, E. Laermans, and I. Moerman, *Cooperation techniques between LTE in unlicensed spectrum and Wi-Fi towards fair spectral efficiency*, SENSORS, vol. 17, no. 9, 2017

[5] A. Garcia-Saavedra, P. Patras, V. Valls, X. Costa-Perez, D.J. Leith, *ORLA/OLAA: Orthogonal coexistence of LAA and WiFi in unlicensed spectrum*. IEEE/ACM Transactions on Networking, 26(6), 2665-2678.

[6] M. M. Sohul, M. Yao, T. Yang and J. H. Reed, "Spectrum access system for the citizen broadband radio service," in IEEE Communications Magazine, vol. 53, no. 7, pp. 18-25, July 2015. doi: 10.1109/MCOM.2015.7158261

[7] P. Hintjens, *ZeroMQ Messaging for Many Applications*, O'Reilly Media, March 2013.

[8] National Instruments, *Overview of the NI USRP RIO Software-Defined Radio*, White Paper, December 2015. [online]. Available: http://www.ni.com/white-paper/52119/en/

[9] Ettus Research LLC, *USRP Hardware Driver*, [online]. Available: http://files.ettus.com/manual/

[10] Ettus Research LLC, *Products*, [online]. Available: https://www.ettus.com/product

[11] Ismael Gomez-Miguelez, Andres Garcia-Saavedra, Paul D. Sutton, Pablo Serrano, Cristina Cano, and Doug J. Leith. 2016. srsLTE: an open-source platform for LTE evolution and experimentation. ACM, New York, NY, USA, 25-32. DOI: https://doi.org/10.1145/2980159.2980163

[12] Mennes, R., Claeys, M., De Figueiredo, F. A., Jabandžić, I., Moerman, I., & Latré, S. (2019). Deep Learning-Based Spectrum Prediction Collision Avoidance for Hybrid Wireless Environments. IEEE Access, 7, 45818-45830.

[13] Camelo, M., Shahid A., Fontaine, J., De Figueiredo, F., De Poorter, E., Moerman, I., & Latré, S. (2019). A Semi-Supervised Learning Approach Towards Automatic Wireless Technology Recognition, IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN), Newark, NJ, USA, 2019.

[14] Sravanthi Kanchi, Shubhrika Sandilya, Deesha Bhosale, Adwait Pitkar, and Mayur Gondhalekar, *Overview of LTE-A technology*, IEEE Global High Tech Congress on Electronics (GHTCE), March 2014.

[15] A. Shahid, J. Fontaine, M. Camelo, J. Haxhibeqiri, M. Saelens, Z. Khan, I. Moerman, E. De Poorter, A Convolutional Neural Network Approach for Classification of LPWAN Technologies: Sigfox, LoRA and IEEE 802.15. 4g, 2019 16th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON). IEEE, 2019.

[16] V. Maglogiannis, A. Shahid, D. Naudts, E. De Poorter, and I. Moerman, "Enhancing the Coexistence of LTE and Wi-Fi in Unlicensed Spectrum Through Convolutional Neural Networks," IEEE Access, vol. 7, pp. 28464-28477, 2019.