OpenAirMesh—An Experimental Platform for Cooperative Mesh Networks

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***Abstract*—OpenAirInterface (www.openairinterface.org) is an experimental real-time hardware and software platform for air-interface experimentation. It comes in two configurations, cellular and cooperative mesh network topologies. Here we present the platform architecture for mesh networks. The network is organized in clusters, where dynamically-allocated cluster-heads (CHs) manage radio resources. CHs are typically the best-connected nodes in a particular geographical area and are synchronized in a distributed fashion by using special relaying nodes on the cluster boundaries.**

The physical (PHY) layer of the platform targets WiMax and UMTS LTE like networks and thus uses MIMO-OFDMA as modulation and multiple access technique. The current hardware supports 5 MHz bandwidth and two transmit/receive antennas. The media access (MAC) layer of the platform supports an abundant two-way signalling for enabling collaboration, scheduling protocols as well as traffic and channel measurements. The platform is designed for a full software-radio implementation, in the sense that all protocol layers run on the host PCs under the control of a Linux real time operation system.

Applications of the OpenAirMesh platform include demonstration of broadband ad hoc communications systems for public safety units as well as demonstration of collaborative communication in a cognitive radio system. In addition to the basic architecture of OpenAirMesh we highlight some application examples.

I. Introduction

Wireless mesh networks (WMNs) consist of a set of nodes, where each node operates not only as a host but also as a router, forwarding packets on behalf of other nodes that may not be within direct wireless transmission range of their destinations. A WMN is dynamically self-organized and self-configured, with the nodes in the network automatically establishing and maintaining mesh connectivity among themselves (creating, in effect, an ad hoc network). This feature brings many advantages to WMNs such as low up-front cost, easy network maintenance, robustness, and reliable service coverage [1].

WMNs can use cooperative transmission to greatly increase power efficiency, reliability and throughput. Such techniques refer to scenarios where one or more relay nodes are used to perform some type of distributed spatial processing technique, such as space-time coding [2], [3] or distributed Hybrid-Automatic-Repeat-Request (HARQ) protocols [4], [5]. Despite recent advances in wireless mesh networking and cooperative diversity, many research challenges remain in all protocol layers. Easily reconfigurable testbeds are a convenient way to investigate new ideas and to tackle many of these problems at an early development stage. This paper presents the Eurecom testbed OpenAirMesh, which is an experimental real-time hardware and software platform for cooperative mesh networks. This effort can be seen as a mock standard for realistic experimentation purposes which retains the salient features of a real radio system, without all the required mechanisms one would find in a standard used in deployment of commercial networks.

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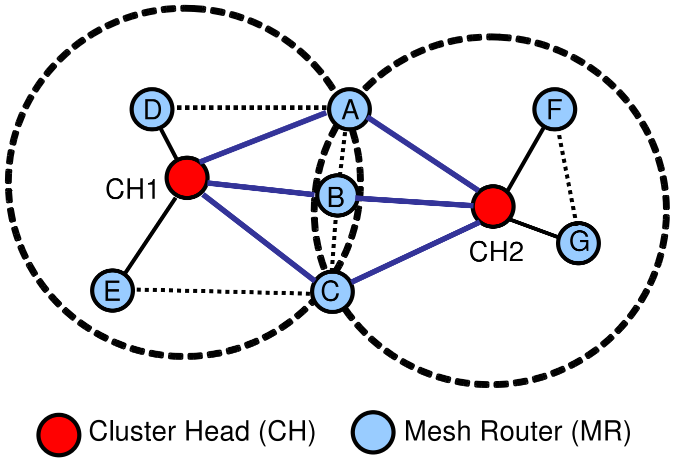

Fig. 1. The mesh network topology is organized in clusters. Each cluster is controlled by a cluster head (CH). Other nodes in the network are called mesh routers (MR) since they can be used to relay information between CHs in a collaborative way (thick solid line). Communication is possible between CH and MR (thin solid line) and between MRs within one cluster (thin dashed line).

The rest of the paper is organized as follows. Section II presents the basic network topology and the hardware architecture of the OpenAirMesh testbed. Sections III and IV focus on the properties of the physical and media access layer respectively. Finally we give some application examples in Section V. We conclude the paper in Section VI.

II. Network and Hardware Architecture

A. Network Topology

Figure 1 depicts the general architecture of the mesh broadband network. We distinguish different types of nodes, namely Cluster Head (CH) and Mesh Router (MR).

a) Cluster Head: The primary role of the CH is to manage radio resources in their cluster, much as a basestation would in a cellular network. The cluster is defined as the set of nodes which are characterized by one-hop connectivity with the CH. CH can only be connected to MR on the same frequency-carrier since they use the same temporal resources as other CH. Thus direct CH $\leftrightarrow$ CH communication is not possible on the same frequency carrier. The downlink (CH $\rightarrow$ MR) signalling channels allow for the CH to schedule transmission of labels (in the form of time and frequency mappings on the radio resource) which each carry different types of traffic throughout the mesh network according to pre-defined quality-of-service (QoS) descriptors. The Uplink (UL) signalling channels (MR $\rightarrow$ CH) are used for relaying bandwidth requirement indicators and channel quality measurements from nodes within the cluster. These feed the scheduling algorithms residing in the CH and allow for proper resource allocation satisfying QoS negotiations carried out using Layer 3 (L3) signalling. The latter are beyond the scope of the description in this paper.

b) Mesh Router: The primary role of an MR is to interpret the scheduling information from the CH on the DL signalling channels in order to route the traffic corresponding to the scheduled labels on the allocated physical resources. MR can be connected to other MR (direct link) in the same cluster. MR can also be connected to more than one cluster at the same time. It is also expected to using the UL signalling channels to relay measurements (both traffic and radio signal) to the CH with which it is connected.

B. Hardware Architecture

Currently, the hardware used for the reference implementation of OpenAirMesh consists of dual-RF CardBus/PCMCIA data acquisition cards called CardBus MIMO I. The RF section is time-division duplex and operates at 1.900-1.920 GHz with 5 MHz channels with 21dBM transmit power per antenna for an OFDM waveform. EURECOM has a frequency allocation for experimentation around its premises in Sophia Antipolis. The cards house a medium-scale FPGA (Xilinx X2CV3000) allowing for an embedded HW/SW system implementing the physical layer. Besides implementation in the FPGA, for advanced PHY algorithms and real-time testing prior to HW implementation, the PHY layer is usually run in real-time on the host PC under the real-time operating system (RTOS) RTAI.

A successor to CardBus MIMO I is currently under development and will be available for use at the beginning of 2009. It comprises two parts: Express MIMO, which is the baseband processing unit, and Agile RF, which is the RF unit. Agile RF will offer significantly more RF functionality in terms tuning range and channel bandwidth. The tuning range per RF chain is 180MHz-8GHz with 20MHz channels. In addition, FDD communication will also be possible. The Express MIMO card will provide significantly more processing power for intensive signal processing and interfacing to partner DSP engines. It will house 4 high-speed A/D and D/A converters. More information can be found on the openairinterface.org website.

III. Physical Layer

The physical (PHY) layer of the platform targets WiMax and UMTS LTE like networks and thus uses multiple-input multiple-output orthogonal frequency division multiple access (MIMO-OFDMA) as modulation and multiple access technique. The actual parameters and mechanisms can be configured prior to deployment of the equipment or potentially over-the-air, although the latter is not yet supported by any of the OpenAir MAC implementations.

The MIMO-OFDMA system provides the means for transmitting several multiple-bitrate streams (multiplexed over subcarriers and antennas) in parallel. Moreover, PHY signaling strategies are included to provide the means for exploiting channel state feedback at the transmitters in order to allow for advanced PHY allocation of OFDMA resources via the MAC.

This section describes the physical and transport channels, the framing and channel multiplexing, the coding and modulation scheme, as well as the synchronization procedure.

A. Physical and Transport Channels

OpenAirMesh uses a layering architecture which strongly resembles that of an ETSI standard, in the sense that data and control traffic flows use radio bearers, logical, transport and physical channels. Here we are concerned primarily with the MAC and PHY layer description, and thus the transport channel interface. This encompasses the control and user plane interfaces between the MAC and PHY layers and is composed of the following entities

- The **CH broadcast channel (CH-BCH)** is a broadcast control channel which houses MAC-layer signaling for CH and MR physical resource scheduling as well as layer 2 radio-resource control (RRC) signalling for topology and QoS management.
- The **CH Scheduled-Access Channel (CH-SACH)** is a data channel (for both control and user-plane logical channels) used by CH to communicate with a node in its cluster. It can be configured as a multicast flow or as a unicast flow with an associated MR-SACH in the reverse direction originating in the corresponding node.
- The **MR broadcast channel (MR-BCH)** is a broadcast resource used by MR to extend the coverage of a cluster during topological discovery.
- The **MR Scheduled-Access Channel (MR-SACH)** is a data channel (for both control and user-plane logical channels) used by MR to communicate with a node in one of the clusters with which the MR is associated. It can be configured as a multicast flow or as a unicast flow with an associated MR-SACH or CH-SACH in the reverse direction originating the corresponding node. It uses the physical resources allocated by the CH in the CHBCH and is always bundled with an MR-SACCH.
- The **MR Scheduled-Access Control Channel (MR-SACCH)** is a MAC-layer signalling channel associate to a particular MR/CH-SACH used to provide PHY modulation formats for the corresponding MR-SACH in the current TTI as well as feedback information for the HARQ processes and channel quality indicators for the corresponding pair MR-SACH/CH-SACH in the reverse direction.

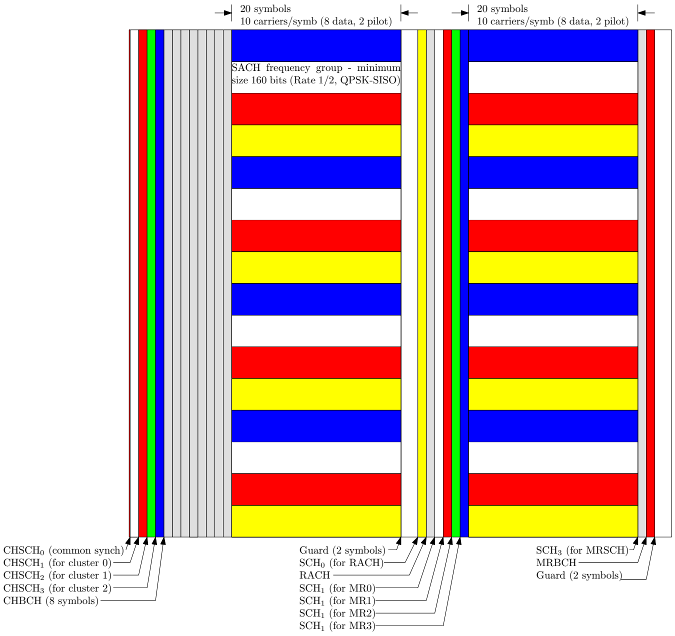

Fig. 2. Mesh frame structure

Sampling rate	7.68 Msamp/s
Symbol (DFT/IDFT) size	256 samples
Prefix length	64 samples (8.33μs)
Useful carriers	160
Number of subbands (chunks)	16
Data carriers per subband	8
Pilots per subband	2

TABLE I
NOMINAL OFDMA PARAMETERS IN OPENAIRMESH

- The **Random-Access Channel (RACH)** is a signalling channel used by a MR during the association phase with the CH.

Each of the transport channels is mapped to a corresponding physical channel of the same name. In addition, two other physical channels used for parameter estimation are also available:

- The **Physical CH Synchronization Channel (CHSCH)** is a pilot resource reserved to a CH which is responsible for delivering synchronization information to nodes in the cluster. This channel is used by nodes to acquire timing information regarding the beginning of the TTI and to perform initial frequency offset adjustments with respect to the carrier frequency of the CH. The channel is also used by adjacent CHs to synchronize the network, in order to facilitate inter-cluster communication under quality-of-service guarantees.
- The **Physical Synchronization Channel (SCH)** is a pilot resource used by a node to allow the CH to estimate the channel of an MR/UE.

B. Framing and Channel Multiplexing

The physical resources are organized in frames of OFDM symbols. OpenAirMesh framing is completely configurable, but the nominal OFDMA configuration is shown in Table I. One frame consists of 64 OFDM symbols and is divided in a CH transmission time interval (TTI) and a MR TTI (see Figure 2). The first four symbols of the CH TTI are reserved for pilot symbols. Each CH transmits one common pilot symbol ($CHSCH_0$) at position 0 and one dedicated pilot symbol ($CHSCH_i$) at position $i \in \{1, 2, 3\}$. This way we can ensure orthogonality between the pilots of different CH received at one MR. The pilot symbols are followed by the broadcast channel (CH-BCH). The rest of the CH TTI frame is reserved for the multiplexed scheduled access channels (CH-SACH).

The MR TTI contains the random access channel (MR-RACH) with an associated pilot symbol (SCH_0). Each MR transmits one pilot symbol SCH_i, $i \in \{1, 2, 3, 4\}$. This way we can ensure orthogonality between the pilots of different MR received at one CH. The pilot symbols are followed by the multiplexed scheduled access channels (MR-SACH) and a broadcast channel (MR-BCH) with an associated pilot symbol (MRSCH). The end of the CH and MR TTIs are protected by a guard interval of two symbols. All pilots are designed for MIMO and/or Multiuser channel estimation at the corresponding end.

C. Network Synchronization Procedure

The OpenAirMesh network supports full time synchronization. Synchronization is achieved by declaring one CH to be the primary CH, which is the reference clock in the system. Every MR within this cluster synchronizes to the CH using the CHSCH. The MR then sends out a synchronization signal itself (the MRSCH) to allow a secondary CH to initially synchronize to the network. As soon as a secondary CH is synchronized to the network, it also sends out a CHSCH. The MR can now track the CHSCH from both CHs and keep them synchronized. When the CHs begin drifting apart, it is the MR's responsibility to resynchronize them using a timing adjust message to the one lagging behind using higher layer signaling. This type of distributed synchronization can be interpreted as a form of *firefly synchronization* [6], [7].

We now sum up the initial synchronization procedure during network establishment. When a node is turned on, it first looks for a $CHSCH_i$ $i = 1, 2, 3$ and tries to decode the corresponding CHBCH. If successful it declares itself synchronized to CHSCH and becomes a MR. Otherwise it looks for a MRSCH and tries to decode MRBCH. If successful, it declares itself synchronized to MRSCH and becomes a secondary CH. Otherwise it becomes a primary CH.

D. Coded Modulation & HARQ

OpenAirMesh makes use of punctured binary codes (64-state rate 1/2 convolutional or 8-state rate 1/3 3GPP/LTE Turbo code). Puncturing can use either 3GPP rate matching or random puncturing in order to fine tune the coding rate to adapt to configurable transport block sizes delivered to PHY by the MAC. The overall coding sub-system is shown in Figure 3. New transport blocks arriving from the MAC layer (based on multi-user scheduling) are coded using a CRC extension and the chosen binary code. These are then fed to the active transport block buffer along with those that are to be retransmitted. Each transmitted block is punctured and then passed to a bit-interleaver and modulation mapper (BICM). OpenAirMesh supports QPSK, 16-QAM and 64-QAM modulation.

The transmitted transport blocks can be split into to two spatial streams in the case of point-to-point MIMO transmission. Each stream receives an adjustable amplitude and then each is passed to a different (orthogonal) space-time parser which guarantees that both streams use different antennas in the same time/frequency dimension. This allows for low-complexity successive interference cancellation (SIC) and detection at the receiver and maximizes diversity against fading [8]. This is a form of superposition coding since the two streams are combined additively in the air through the use of multiple transmit antennas.

A second design objective for this coding strategy, in addition to low-complexity point-to-point MIMO operation, is that the same transmitter and receiver structure can be used in a distributed MIMO scenario. Here one spatial stream is used at each source and the second stream originates in another part of the network, either in the same cluster or an adjacent cluster. Co-operation is needed in order to guarantee different space-time-frequency (STF) parsing for the two streams so that they can be decoupled at the SIC receiver. A particular user can decode both streams or simply select the one it requires. Examples of this are discussed further in Section V.

IV. Layer 2 Protocol Stack

The OpenAirMesh Layer 2 protocol stack comprises:

- A IP/MPLS networking device (NAS DRIVER) responsible for provision of IP/MPLS layer services to Layer 2 and vice-versa
- A Radio resource control (RRC) entity responsible for MAC layer signalling for configuration of logical channels and retrieval of measurement information.
- A Radio Link Control (RLC) entity which is responsible for automatic repeat request protocols (ARQ) and IP packet segmentation
- A convergence protocol (PDCP) responsible for IP interface and related functions (header compression, ciphering, etc.)
- A scheduling and multiplexing unit to controll the media access (MAC).

An overview of the layer 2 protocol stack for a CH is shown in Figure 4 and a subset of these entities are described in the following subsections.

A. Radio Resource Control (RRC)

The radio resource control entity is responsible for the L2 signalling implementing the radio bearer establishment and maintenance through the control of measurement procedures. Its internal state machine controls the basic procedures for startup, monitoring of synchronization through the measurement system and update of the node's role in the network. RRC is responsible for configuration of all layer 2 entities (and PHY via MAC), both dynamic (during flow establishment) and static (control channels). This functionality is in response to events occurring in the interaction with L3 and based on dynamic measurements of radio quality and traffic intensity.

B. Radio Link Control (RLC)

The RLC segments IP packets. The segment size is configurable for each QoS class and is signalled by higher layers during route establishment. The sizes are chosen based on the granularity of the underlying MAC/PHY resources (transport blocks). RLC is responsible for ARQ and indexing of SDUs from the user traffic and signalling SDUs from RRC. The SDU inputs from PDCP form the set of radio bearers, and those from RRC the set of signalling radio bearers. It has three modes of functionality: acknowledged (AM), unacknowledged (UM) and transparent (TM). Each logical channel in AM has an associated selective-repeat ARQ process which is managed by RLC which is meant to provide a third level of error recovery with respect to the FEC offered by PHY and HARQ by MAC. The ARQ mechanisms are based on Release 6 3GPP RLC (25.322) specifications. The interface with RRC serves for the configuration of the radio bearer. The interface with MAC is designed such that data for each logical channel is buffered in data queues, whose occupancy can be measured by the MAC scheduling entity.

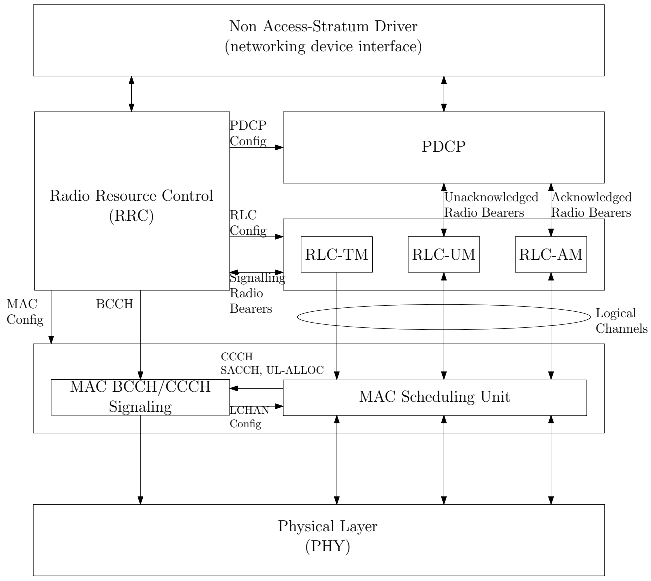

Fig. 4. OpenAirMesh CH Layer 2 Protocol Stack

C. MAC Scheduling Entity (MAC)

The MAC layer scheduling and multiplexing entity is responsible for scheduling control plane and user plane traffic on the physical OFDMA resources. On transmission, the inputs to this entity are connected to data queues originating in the RLC layer which form the set of logical channels. The control plane traffic is represented by the following logical channels:

- Broadcast Control Channel (BCCH) : This resource is a low bit-rate control channel used by an CH for broadcasting basic information to nodes in the cluster.
- Common Control Channel (CCCH) : This resource is a low bit-rate control channel used both during the attachment or association phase of a new node.
- Dedicated Control Channel (DCCH): This is a resource used to relay access-layer signaling information (RLC return channels, RF measurement reporting, traffic measurement reporting, power control, etc.) to the corresponding node.

The user plane traffic is represented by the following logical channel:

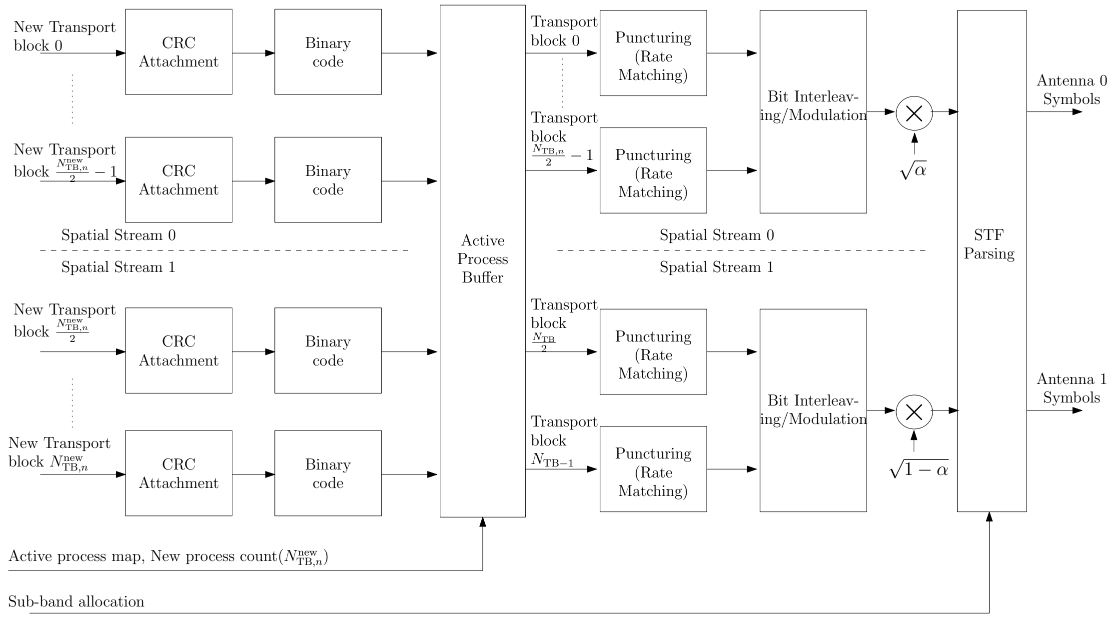

Fig. 3. OpenAirMesh Coded Modulation and HARQ

- Dedicated Traffic Channel (DTCH): This resource is a variable bit-rate traffic channel with negotiated QoS parameters used by the mesh network to transport data traffic corresponding to a particular flow.

It is important to note that although dedicated resources are configured at the input of the MAC layer, the physical resources allocated in the scheduling entities (with exception of the CHBCH) are dynamically allocated every CH TTI and thus all physical resources are shared. The BCCH is multiplexed in the scheduling entity responsible for generation of the CH-BCH transport channel along with MAC-layer signalling. MAC signalling concerns both allocations of CH-SACH in the current frame and MR-SACH in the next frame (uplink, downlink and direct link map of PHY resources). The CCCH (uplink) is used exclusively during the attachment phase of the MR with a particular cluster and corresponds to the only random-access resources allocated by the CH in the frame.

The DCCHs are multiplexed along with user-plane traffic DTCHs on the available CH-SACH resources. Based on measurement and feedback information, SACH scheduling (see Figure 5) aims to respect the negotiated QoS of each logical channel, while maximizing the aggregate spectral efficiency of the data streams. Different wideband scheduling policies taking into account both queuing measures from RLC and channel quality feedback can be accommodated (see for instance [9]). Channel quality information is signalled between corresponding MAC-layers based quantized wideband channel estimates received from PHY.

As a general rule, DCCH and CCCH do not use HARQ, since they are signaling channels which use the lowest spectral efficiency modulation. DTCH generally uses HARQ with a maximum number of retransmission rounds determined by higher layer configuration (i.e., the delay class in the QOS requirement). SACH scheduling makes use of up to 16 parallel HARQ Type-2 processes per logical channel in order to maximize throughput and benefit from superior channel conditions.

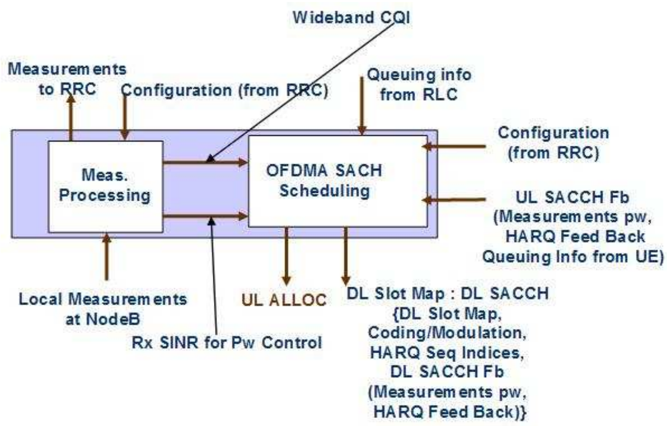

Fig. 5. Overview of the MAC Scheduler

V. Experiments and Applications

As OpenAirMesh implements the PHY and the MAC layer completely in software it is very flexible and open for a variety of experiments. In this section we highlight some of the planned activities for indoor and outdoor demonstration of cooperative communication schemes in 2008–2009.

A. Inter/Intra Cluster Interference Cancellation

The key ingredient for allowing spatial reuse in wireless networks is interference mitigation. This can be achieved first by collaborative resource allocation, which in OpenAirMesh can be achieved by collaboration in the scheduling algorithms of adjacent CHs. This is made possible with network synchronization which has already been demonstrated with the OpenAirMesh platform as described in Section III-C. As a result we will investigate the practicality of interference-aware scheduling. A second method is through interference cancellation using multi-antenna receivers. This allows for three interference cancellation scenarios:

1) MRs which communicate concurrently with two CHs (one stream for each CH on transmit and receive), for instance node A communicating with CH1 and CH2 in Figure 1.
2) CH scheduling of concurrent direct links on opposite ends of the same cluster, for instance communication A→D concurrently with communication C→E.
3) Mitigation of independent (but synchronous) streams in adjacent clusters.

Such schemes rely on the ability to perform efficient detection in the presence of an interfering signal. Here again, network synchronization combined with the superposition based coded-modulation formats described in III-D allow for efficient dual-stream detection with multi-antenna receivers. PHY receiver structures performing such detection have been developed and are currently being integrated onto the platform equipment [8].

B. Multiple Relay Channel

An example of a multiple relay channel is shown in Figure 1, where the CH1 and CH2 act as source and destination respectively and MRs A, B, and C act as relays. Note that there is no direct link between CHs in this example. Multiple relays can significantly improve the reliability of the communication between CHs by exploiting cooperative diversity schemes such as distributed space-time coding [2], [3] or collaborative beamforming [10]. Such a scenario could be beneficial for secure robust mesh networks where link redundancy is accomplished seamlessly by the PHY/MAC layer. Here we would like to investigate a practical mechanism for providing distributed PHY-layer relaying and the consequences on design aspects related to spatial HARQ and channel coding mechanisms.

While distributed space time coding requires timing synchronization at the symbol level only, collaborative beamforming schemes require exact phase synchronization. In the first case, the timing synchronization procedure described in Section III-C can be used to guarantee synchronization on a symbol level (slight timing offsets not exceeding the cyclic prefix length are absorbed by the OFDM modulation scheme). For the latter case, more sophisticated schemes must be used to achieve proper phase synchronization. A promising approach is given by [11]. However, to make their algorithm work in a real system, one must also take the non-symmetric characteristics of the RF electronic circuitry into account [12].

C. Target Applications

One major application of OpenAirMesh platform is the demonstration of rapidly-deployable broadband ad hoc communications systems for public safety units in interventions following natural hazards and industrial accidents. Such public safety units require a reliable communication broadband system and services that do not need heavy management operations involvement in order to allow them to increase their efficiency during their critical interventions. Here the elements of the mesh network are routers, some of which are edge routers in the sense that they are gateways to other networks (WIFI, bluetooth, etc.). These are some of the application scenarios considered in the CHORIST FP6 project (www.chorist.eu) and future HNPS Celtic project.

Another application of OpenAirMesh is the demonstration of collaborative communication in a sensor network. One example of such a sensor network scenario would be cognitive radio architecture described in the FP7 SENDORA project. Such a sensor network can be employed to detect "holes" in the spectrum in some geographical region which can then be used by a cognitive radio [13].

VI. Conclusions

We have presented OpenAirMesh, an experimental real-time hardware and software platform for wireless mesh networks. The specification of the MAC and PHY layer allows for the implementation of different cooperative communication schemes, such as inter- and intra-cluster interference cancellation, spatial HARQ and distributed space-time coding. The distributed timing synchronization algorithm and the collaborative MAC scheduling algorithm presented in this paper are prerequisites for conducting those experiments. Applications of the OpenAirMesh platform include demonstration of broadband ad hoc communications systems for public safety units as well as demonstration of collaborative communication in a cognitive radio system.

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