Developing an Innovative Multi-hop Relay Station Software Architecture in the Scope of the REWIND European Research Programme

Konstantinos N. Voudouris[1], Ioannis P. Chochliouros[2], Panagiotis Tsiakas[1], Avishay Mor[3], George Agapiou[2], Avner Aloush[3], Maria Belesioti[2], and Evangelos Sfakianakis[2]

[1] Technological Educational Institution (T.E.I.) of Athens, Dept. of Electronics
Ag. Spyridonos & Milou 1 Street, 12210 Egaleo, Athens, Greece
kvoud@ee.teiath.gr
[2] Hellenic Telecommunications Organization (O.T.E.) S.A., Research Programs Section, 99, Kifissias Avenue, 15126 Maroussi, Athens, Greece
ichochliouros@oteresearch.gr
[3] DesignArt Networks Ltd., Ha'Haroshet Street, P.O. Box 2278, Ra'anana, Israel
avishaym@designartnetworks.com

Abstract. In the scope of the REWIND European Research Program we propose a Multi-Hop Relay network architecture, based on the recently developed IEEE 802.16j standard with the aim of enhancing throughput, network coverage and capacity density. In particular, we provide an essential description of the Relay Station Software architecture design, mainly focused on the PHY and MAC layers architecture, by analyzing the essentials of the downlink and uplink data flows, on the basis of the corresponding relay node to be included in the wireless network.

Keywords: Control and Data Flow, IEEE 802.16j standard, MAC layer, Multi-hop Relay, PHY layer, Relay Station (RS), WiMAX.

1 Introduction

Wireless communication has become a "hot topic" in IT (Information Technology) and CT (Communication Technology); personal broadband is currently considered as one of the *most emerging* and *most promising* services in the global area of wireless communications. Due to the introduction/deployment of innovative facilities (such as video-on-demand (VoD), on-line gaming and e-learning) and the continuously increasing abundance of numerous portable devices (such as PDAs (personal digital assistants) and smart-phones), the need for ubiquitous connectivity and coverage has now become a necessity. Towards fulfilling that purpose, WiMAX (Worldwide Interoperability for Microwave Access), as a robust and reliable innovative technology, enables users to enjoy the same experiences they have at home

F. Granelli et al. (Eds.): MOBILIGHT 2009, LNICST 13, pp. 160–172, 2009.

or in the office wherever they go, at affordable prices[1]. Activity in the relevant sector continues very fast: i.e. products are reaching in the market, networks are being rolled-out and service offerings are still developing, under various scenarios. WiMAX technology has the potential to be an important component of future converged (or ubiquitous) networks due to its reach and the relatively high-speed wireless connectivity and service availability. In fact, operators have to face (and are still struggling with) a number of major challenges, such as increased system capacity with better coverage; moreover, they have to deliver new and innovative, "value-added" services ever-improving performance features. Finally, all previous concerns are strongly bundled with lower network cost per subscriber.

The term "repeater" (or "relay") originated with telegraphy and referred to an electromechanical device, used to regenerate related signals. Use of the term has continued in telephony and data communications. So, a repeater is an electronic device that receives a signal and retransmits it at a higher level and/or higher power, or onto the other side of an obstruction, so that the signal can cover longer distances without degradation. In telecommunications, the term "repeater" has the following wider standardized meanings: (i) An analogue device that amplifies an input signal regardless of its nature (analogue or digital); (ii) A digital device that amplifies, reshapes, retimes, or performs a combination of any of these functions on a digital input signal for retransmission. Thus, in digital communication systems, a repeater receives a digital signal on an electromagnetic or optical transmission medium and regenerates it along the next leg of the medium. In electromagnetic media, repeaters overcome the attenuation caused by free-space electromagnetic-field divergence or cable loss. A series of repeaters make possible the extension of a signal over a longer distance. Repeaters can "remove" the unwanted noise in an incoming signal. Unlike an analogue signal, the original digital signal, *even if weak or distorted*, can be clearly perceived and restored. With analogue transmission, signals are re-strengthened with amplifiers, which unfortunately also amplify noise. Because digital signals depend on the presence (or absence) of voltage, they tend to dissipate faster than analogue ones and need more frequent repeating. Whereas analogue signal amplifiers are spaced at 18,000 meter intervals, digital signal repeaters are typically placed at 2,000-6,000 meter intervals.

As far as WiMAX is concerned, the repeater is a two-way radio transceiver system designed to provide coverage of "dark zones" not served by WiMAX base stations (i.e. areas where coverage gaps are detected), bypassing direct Line-of-Sight (LOS) obstacles between a base station (BS) and a number of remote terminals or extending coverage beyond the BS limits. A typical WiMAX repeater is composed of two outdoor transceivers (local and remote), specifically designed to minimize the cable running to each antenna and the implicit signal degradation, as well the induced signal delay. The only connection requirement from the outside is a power feed. Each transceiver executes a transparent retransmission of the signal on each way. A frequency offset mechanism avoids co-channel interference and "eases" the frequency planning process, while an ALC (Automatic Level Control) provides a stable signal regardless

1 Related work is performed by the WiMAX Forum, an organization with more than 150 member-companies with the goals of promoting worldwide adoption of the IEEE 802.16 air interface standard and to develop a suite of conformance tests to ensure equipment interoperability. [www.wimaxforum.org]

of weather and other transient conditions. Thus, a repeater is used to enhance signals between mobile user equipment and a BS, to extend the coverage of a single BS and so to solve design problems and performance issues (for small areas).

The EU-funded "*REWIND*" Project (*ICT-FP7, Grant Agreement No.216751*) examines issues of relay station implementations for WiMAX, as such technology is currently the "most advanced" wireless one available for deployment, and many of its aspects are likely to be implemented in any 4G wireless technology. Relay stations standardization has already commenced by the IEEE under the "Multi-hop Relay Task Group" also known as *802.16j Task Group*. The intention of the REWIND Project is to support this standard process, through direct participation and through research and development of relay technology and products in order to assist the standard body with interoperability, laboratory and field information on possible implementations of the WiMAX relay. REWIND will proceed to the algorithmic research and technology development of the mobile multi-hop WiMAX relay networks in order to increase coverage and throughput issues. Part of its actual work is responsible for the design of the novelty software (SW) and hardware (HW) functional areas of the corresponding Relay Station (RS) product, which includes algorithmic research and simulations, system architecture and requirements specifications, and appropriate software code development and integration. In the scope of the present work, Section 2 deals with essential architectural features of relay-based networks. Section 3 focuses on fundamentals of the 802.16j protocol stack while Sections 4 emphasizes on control and data flow issues of the essential REWIND-based architecture.

2 Architecture of Relay-Based Networks

In order for the next generation of wireless technology to be able to deliver ubiquitous broadband content, the network is required to offer excellent coverage (both outdoor and indoor) and significantly higher bandwidth per subscriber. To achieve this at frequencies above 2 and 3 GHz (as these are "targeted" for future wireless technologies), network architecture must reduce significantly the cell size or the distance between the network and subscribers' antennas.

The principal element in all wireless networks is the "cell". A cell is a region of radio reception that is a part of a larger radio network and is served by a fixed transmitter called the Base Transceiver Station (BTS or BS) which is controlled by the Base Station Controller (BSC). As the cell size becomes smaller the number of subscribers served per unit area is increased or higher bit rates can be provided for services [1]. Additionally, the size of the BS equipment as well that of antennas is reduced, since the transmitted power is lower in order to keep the cell dimensions small, replacing bigger equipment and thus making installation easier. Another benefit compared to larger cells (e.g. macro-cells) is smaller site acquisition costs and easier to obtain planning permissions [2]. While micro-, pico- and femto-BTS technologies reduce the cost of BS equipment, they all still depend on a dedicated backhaul which results in significant capital expenditures (CAPEX) and operating expenditures (OPEX) to the network operator. The wireless multi-hop relay station solution is designed to overcome such limitations.

Although relay technologies are not an entirely new concept [3], large-scale deployment of standardised related technology is new. Thus, there is a need for new approaches to network planning [4]. Multi-hop Relay (MR) is a deployment that may be used to provide additional coverage or performance advantage in access networks. In MR networks, the Multi-hop Relay BS (MR-BS) is connected to several RSs, in a "multi-hop topology", to enhance the network coverage and capacity density [5].

Traffic and signalling between the Subscriber Station-SS[2] (i.e., the equipment set providing connectivity between subscriber equipment (potentially including customer premises equipment-CPE and a BS) and MR-BS are relayed by the RS thereby extending the coverage and performance of the system in areas where RSs are normally deployed. Each RS is under the supervision of an MR-BS. In a system with more than two hops, traffic and signalling between an access RS and MR-BS may also be relayed through intermediate RSs. The RS is fixed in location. The SS may also communicate directly with the MR-BS.

Fig.1 illustrates the MR-BS (connected to an access service network gateway (ASNGW) via a Giga-Ethernet connection) and two-hop RS deployment. For each one of the RSs there is an "access link" (i.e. the radio link between a MR-BS or a RS and a SS) that covers the current cell and a "backhaul link" to the next cell (i.e. the radio link between a MR-BS and RS or between a pair of RSs).

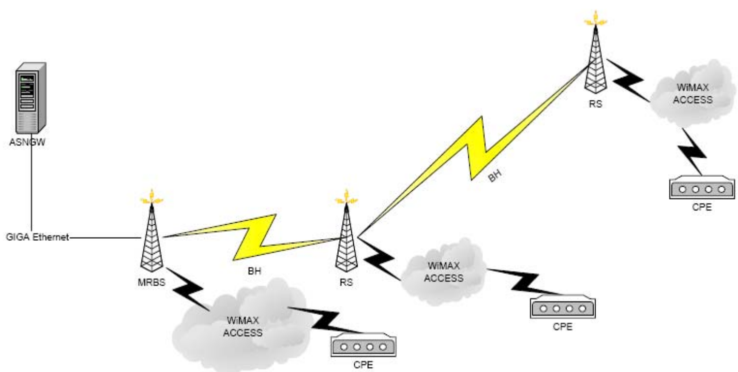

Fig. 1. MR-BS and RSs Deployment

2.1 Relay Scenarios for Network Coverage Extension

The current outlook for the overall broadband market worldwide shows that wireless broadband systems will account for 48% (568 million of 1.175 billion) of broadband subscribers worldwide by 2012, significantly higher than the present 17% (69 million of 407 million) [6]. Despite the prognosis that the number of wired broadband subscribers will continue to increase, it is also estimated that their penetration rate will slow down when emerging markets will be converted in developed ones. And this

[2] The term "subscriber station" can be also met as the "user equipment"-UE. It is also known as "mobile station" (MS).

will happen mainly due to the lack of availability of wired lines and due to their expensive deployment cost. On the other hand, this exactly constitutes an opportunity for the wireless broadband providers [7].

As it is well known in all mobile communications, at a given power and carrier frequency, the available data rate decreases when the distance from a BS increases. In order to achieve a satisfactory radio coverage, high capacity, and advanced service quality, the provider should deploy a network with high base stations density. But, in this case the overall cost will increase dramatically and, *consequently*, the end-user should be obliged to pay more expensive for services, especially in emerging markets. In order to meet the goal of low-cost radio network deployment for both, short-range and wide-area coverage, the deployment concept based on layer 2 (multi-hop) relay nodes appears to be one of the most promising solutions [8].

WiMAX relays can achieve more than simply extending the coverage similar to Wi-Fi Mesh or 3G's technologies. Due to OFDMA (Orthogonal Frequency-Division Multiple Access) waveform [9] -which offers network operators the advantage of being able to operate with the larger delay spread of the NLOS (non-LOS) environment [10] - combined with adaptive modulation, adaptive power management, adaptive sub-channelization methods [11] and finally an adaptive architecture of the network, relays can be a quite useful tool in the hand of the operators. When analyzing a business scenario both for fixed and wireless access, it is informative to breakout the end-to-end network as described below and look separately at its parts, i.e.: (i) Customer Premise Equipment (CPE); (ii) Base Station / Relay Station Infrastructure, and; (iii) Edge, Core, and Central Office (CO) Equipment.

There are several cases where repeaters could be used as an active "part" of the considered network. Forwarding traffic between wireless network nodes is an interesting method to fill "coverage holes" and to improve in-building coverage. For example, at an airport where the need for capacity is high at certain peak periods (e.g. departures, arrivals) a repeater could be used in order to "extend" the coverage area of a powerful BS. A case where coverage extension is essential would be during the set up of a "major" event, e.g. a big festival. Such events are usually set up in the borderlines of already established communities, where the required space would be available, but the network infrastructure might not be as extended to cover the extra space or may not be able to support the sudden temporary increase of users (as at the suburbs of a city). This is the case of "nomadic relay stations" which are brought into effect for temporary cover. These can also be used for emergencies and/or disasters.

The terrain morphology (such as height, density, separation, terrain type – hilly or flat) plays an important part for planning requirements, since in wireless radio planning the accurate prediction of electromagnetic field strengths over large areas, both land and sea and the regional clutter are required. For example, a village which is located at the foothill of a mountain might not be covered sufficiently by a BS at the top of the mountain. In this case a RS placed in between, could solve any coverage-related problem or inconsistency. Indeed, a RS can efficiently enhance coverage and so provides an economically satisfactory solution for the network provider, especially in remote areas where usually small communities are situated and a large investment for a corresponding BS could not be justified. In such cases, where buildings are sparse, the RS will mainly be used for coverage range extension.

In fact there are three sub-environments that should be taken under consideration: The first case concerns the vehicular environment, where high mobility and nomadic devices exist (i.e., the case of a traveller in a train who wants to access the Internet, to use multimedia services and to enjoy video streaming or other novel services). In this particular case a number of distributed repeaters may be located in the outside environment of the vehicle (e.g. on the roof of the train). The bandwidth/capacity offered by the network should be "adequate" to support throughput, compatible with data services required from such moving users. The second case relates to the indoor/outdoor environment, where there are static or medium/high mobility devices, and thus very few repeaters may be required to cover the group of establishments and houses and to form a small network, at which users should have a "proper" access for services. Last but not least, are the suburban areas, meaning little populated and scarcely networked areas (such as schools and private residential houses), where the installation of expensive equipment is not justified and so RS implicates the most appropriate solution. Furthermore, there are rural areas which are scarcely populated areas with insufficient coverage, usually of “outdoor” nature. These environments have often little (or no possibilities) to backhaul high bandwidth connections (e.g. via fixed line copper or fiber links or microwave radio links), and consequently, two alternatives are applicable: Either dedicated high bandwidth microwave connections per base station, or the formation of a mesh-like network by the BSs themselves to forward traffic between base stations with no dedicated backhaul connection. This option significantly reduces deployment costs (i.e. CAPEX and OPEX).

Some other notable attributes of relay-based networks is that they can deploy rapidly with flexibility in placing relays and, *at the same time*, they create multiple protection routes with optimized network load distribution, thus ensuring the ability for better quality of service (QoS). A WiMAX repeater provides cost-effective solution to extend the coverage of a WiMAX BS beyond its boundaries, as it does not hold as much infrastructure requirements (shelter, backhaul, energy consumption, etc.) as in the case of a pure WiMAX BS. In addition, the small size of the repeater reduces real estate requirements and therefore reduces deployment cost. It even can be co-located with already existing cell sites making the network management easier. Wireless low cost infrastructure based systems (such as the proposed WiMAX repeaters) may increase the penetration of communications technology in higher levels [12], resulted many end-users with different needs and demands.

3 Essentials of the IEEE 802.16j Protocol Stack

In WiMAX, the IEEE only defined the Physical (PHY) and Media Access Control (MAC) layers in 802.16 [13]. This approach has worked well for technologies such as Ethernet and WiFi, which rely on other bodies such as the IETF (Internet Engineering Task Force) to set the standards for higher layer protocols such as TCP/IP (Transport Control Protocol / Internet Protocol), SIP (Session Initiation Protocol), VoIP (Voice over Internet Protocol) and IPSec (Internet Protocol Security). The main objective of the IEEE 802.16 standards is to develop a proper set of specifications of the air interface, while the WiMAX Forum defines system’s profile, i.e. a list of selected functionalities for a particular usage scenario and overall network architectures [14].

The sector continues to innovate in many ways; one is the development/promotion of new standards to solve "open" problems. Such an initiative (which is currently of extreme interest) is the development of the *Multi-hop Relay Standard, IEEE 802.16j*. This is being developed to provide low cost coverage in the initial stages of network deployment and increased capacity when there is high utilisation of the network. The standard has been identified with a better feasibility and efficiency due to the similarities in the MAC and PHY layers and the support of fast route change[3]. The standard is expected to have significant impact in new 802.16 rollouts.

When deploying an IEEE 802.16j based WiMAX network, this can be considered as a cellular network since they both have the same design principles [15]. The standard specifies a set of technical issues in order to enhance previous standards with the main objective of supporting relay concepts [16]. The 802.16j standard defines an air interface between a MR-BS and a RS [17]. Its most important technical issues are listed as follows: Centralized vs. distributed control; Scheduling; Radio resource management; Power control; Call admission and traffic shaping policies; QoS based on network wide load balancing and congestion control; Security, and; Management. Besides these issues, when it comes to network deployment the main objective remains the optimal placement of the RSs. Operators are mainly concerned about operating costs, revenues and the pay-off periods for their investments; but the quality of services offered, is also an important issue for them. The IEEE 802.16j protocol layering for a simple RS is shown in Fig. 2.

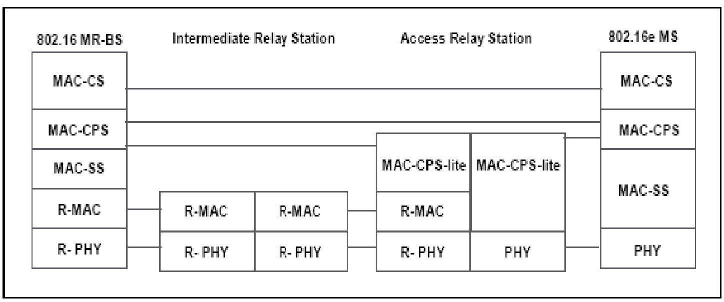

Fig. 2. Depiction of the IEEE 802.16j Protocol Layering for a Simple Relay Station

The principles of the above layers are briefly discussed as follows:

The *MAC Converge Sub-layer (CS)* is primarily used to "map" any data received from the upper layers (e.g. IP, Ethernet) to an appropriate MAC connection, to manage data flow from the upper layer and to ensure that QoS requirements are fulfilled. More specifically, the CS accepts data from the network layer through the CS Service Access Point (SAP) and performs data classification into the appropriate MAC Service Data Units (SDUs). A "classifier" is an entity which selects packets based on the content of packet headers and categorises them according to a set of

---

[3] Harmonized Contribution 802.16j (Mobile Multihop Relay) Usage Models. http://grouper.ieee.org/groups/802/16/relay/docs/80216j-06-015.pdf

"matching criteria" (such as destination IP address). The external higher-layer Protocol Data Units (PDUs) entering the CS are checked against those criteria and accordingly delivered to a specific MAC connection.

The *MAC Common Part Sub-layer (CPS)* is a connection-oriented protocol. Contrarily to previous wireless network technologies (such as IEEE 802.11), it does provide QoS guarantees. It receives the MAC SDUs from MAC SAP; next, it delivers the MAC PDUs to a peer MAC SAP according to the requested QoS, to perform various transport functions (i.e. packing, fragmentation and concatenation). Each MAC PDU is identified by a unique connection identifier (CID). In the scope of past IEEE 802.16 standard versions, in 2004, an operation has been defined where multiple MAC PDUs could be concatenated and comprised into a single burst for transmission purposes. These PDUs had to be encoded and modulated, by using the same PHY (i.e. using the same burst profile); however they could be associated with subscriber stations. The position of each burst into the DL (downlink) frame has been specified by DL-MAP[4], which contained additional Information Elements (IEs). The IEs specify the CID of the receiver, the burst profile used, the start time of the burst and a bit indicating whether an optional preamble is present. The IEEE 802.16e standard has further extended the DL MAP IE of legacy IEEE 802.16, in order to carry the identifiers of multiple connections (CIDs) in a single IE. However, the last missing link for enabling efficient MAC PDU concatenation on relay link is the capability of supporting multiple connections using one uplink (UL) information element. Several approaches have been done to extend the UL MAP[5] IE for relay link.

The *MAC Security Sub-layer (MAC-SS)* handles security issues such as authentication, key exchange and privacy by encrypting the connections between BS and subscriber station. It is based on the Private Key Management (PKM) protocol, which has been enhanced to "fit" the IEEE 802.16 standard. At the time a subscriber connects to the BS, they perform mutual authentication with public-key cryptography using X.509 certificates [18]. The payloads themselves are encrypted by using a symmetric-key system, which may be either DES (data encryption standard) with cipher block chaining or triple DES with two keys.

The *Relay MAC* (*R-MAC) Sub-layer* has been introduced in the IEEE 802.16j standard. It provides efficient MAC PDU relaying/ forwarding and control functions, (such as scheduling, routing, and flow control). It is applicable to the links between MR-BS and RSs and between RSs.

The *Relay Physical (R-PHY) layer* provides definition of physical layer design, (i.e. sub-channelization, modulation, coding, etc.), for links between MR-BS and RS and between RSs. The IEEE 802.16j standard has extended the past IEEE 802.16e frame structure to support in-band BS-to-RS communication. A high level diagram of the 802.16j frame structure in TDD (Time Division Duplex) OFDMA PHY mode is shown in Fig.3. The frame structure supports a typical two-hop relay-enhanced communication, where some MSs are attached to a RS and communicating with a BS via the RS, and some MSs connected directly to the BS.

---

4 Downlink map (DL-MAP) is a MAC message that defines burst start times for both Multihop concept in Time Division Multiplex and Time Division Multiple Access (TDMA) by a subscriber station (SS) on the downlink.

5 Uplink map (UL-MAP): A set of information defining the entire access for a scheduling interval.

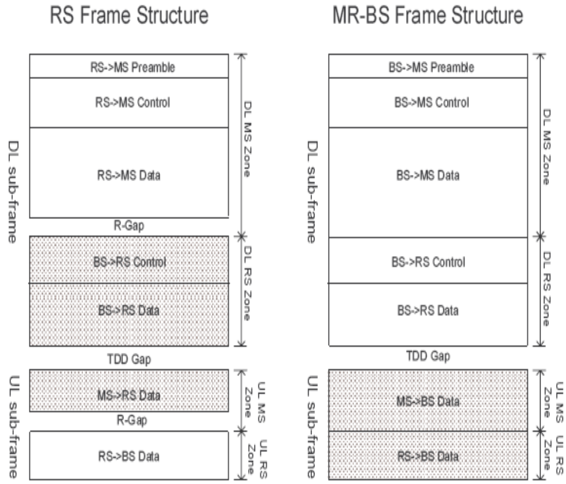

Fig. 3. OFDMA 802.16j Frame Structure

In Fig.3, the horizontal dimension denotes time and the vertical dimension denotes frequency. Frame sections in grey denote receive (Rx) operation, whereas sections in white denote transmit (Tx) operation. The BS and RS frames are subdivided into DL and UL subframes in order to support TDD operation. Both DL and UL subframes are further subdivided into MS and RS zones[6]. The MS zones, supported at both the BS and RS, are backwards compatible with the 802.16e standard. The RS transmits to MSs in its coverage in the DL MS zone and receives control and data from the BS in the adjacent DL RS zone[7]. Each MR-BS frame begins with a preamble followed by a FCH (Frame Control Header) and the DL-MAP and possibly UL-MAP. The DL subframe shall include at least one DL access zone and may include one or more DL relay zones. The UL subframe may include one or more UL access zones and it may include one or more UL relay zones. A relay zone may be utilized for either transmission or reception, but the MR-BS shall not be required to support both modes of operation within the same zone.

4 Control and Data Flow of the Proposed Architecture

The REWIND Project examines RS implementations for WiMAX networks, by proposing the design of the novelty software and hardware functional areas of a WiMAX

[6] For the DL case we can distinguish: (i) The DL access zone (i.e., a portion of the DL subframe in the MR-BS/RS frame used for MR-BS/RS to MS (or "transparent RS transmission"), and; (ii) the DL relay zone (i.e., a portion of the MR-BS/RS to RS transmission). In a similar way, for the UL case we can consider: (i) The UL access zone (i.e., a portion of the UL subframe in the MR-BS/RS frame used for MS to MR-BS/RS transmission), and; (ii) the UL relay zone (i.e., a portion of the UL subframe in the MR-BS/RS frame used for RS to MR-BS/RS transmission).

[7] Detailed structure of the RS zones is under consideration in the IEEE 802.16j Task Group.

Relay station (RS) product. Such a product is to be based on the design of a state-of-the-art SoC (System-on-Chip) silicon platform. The RS shall incorporate all the BS functionality, as well as the relay backhaul and routing functionality, in a single compact, low cost unit. Thus, the Relay node SW shall run all the PHY, MAC, scheduler and networking functionalities, required to operate a complete BS with relay functionality, and to integrate the node into the relay network. We so provide an overview of the RS SW architecture. The corresponding Relay node is based on a highly integrated SoC device, which incorporates all baseband processing (PHY, MAC and CS), networking and control processors required for the Relay station functionality. The RS shall incorporate all the BS functionality, as well as the Relay backhaul and routing functionality. The current section provides a brief overview of the required modules in the RS SW. The host SW is comprised of the following main packages:

- Relay Routing Package: It implements the relay routing connections.
- Frame Manager Package: It implements frame planning and map building.
- Management MAC Package: It implements the 802.16e MAC management procedures.
- DBS (Database) Package: It implements the BS, MSS and connections databases.
- CM (Connection Management) Package: It implements the Connections Management.
- Scheduler Package: It implements Data Delivery Services (QoS).
- Wireless Link Driver (WLD): It implements the drivers to the MAC/PHY machines.
- Backhaul Package: It implements the backhaul links between the MR-BS and RS.
- Configuration Management: It implements configuration parameters.
- RF (radio-frequency) Driver Package: It implements the RF driver.
- ARQ (Automatic-Repeat-Request) Package: Implements the ARQ mechanism.
- HARQ (Hybrid Automatic-Repeat-Request) Package: It implements the HARQ mechanism.
- Network Control package: Implements the R6 control plane.
- Management Package: It implements the unit management (SW upgrade, Telnet[8] and so on).
- Buffer Management Package: It implements the buffers allocation/free management.
- Inter-process Communication: It implements the communication between tasks that reside on different ARM (Advanced RISC Machine)[9] cores.
- Inter-task Communication: It implements the communication between tasks that reside on the same core.
- Boot Loading Package: It implements the boot loading process.
- OSA: It implements the Operating System Abstraction (OSA) Layer.
- ThreadX: High-performance real-time kernel.

Fig.4 describes the Data Flow Diagram (DFD) and the Control Flow Diagram (CFD), as both performed in the scope of the proposed relay station SW architecture

[8] A "*Telnet*" is a terminal emulation program for TCP/IP networks, such as the Internet.

[9] The ARM architecture (previously, the Advanced RISC Machine and prior to that Acorn RISC Machine) is a 32-bit RISC processor architecture that is widely used in embedded designs. Because of their power saving features, ARM CPUs are dominant in the mobile electronics market, where low power computation is a critical design goal.

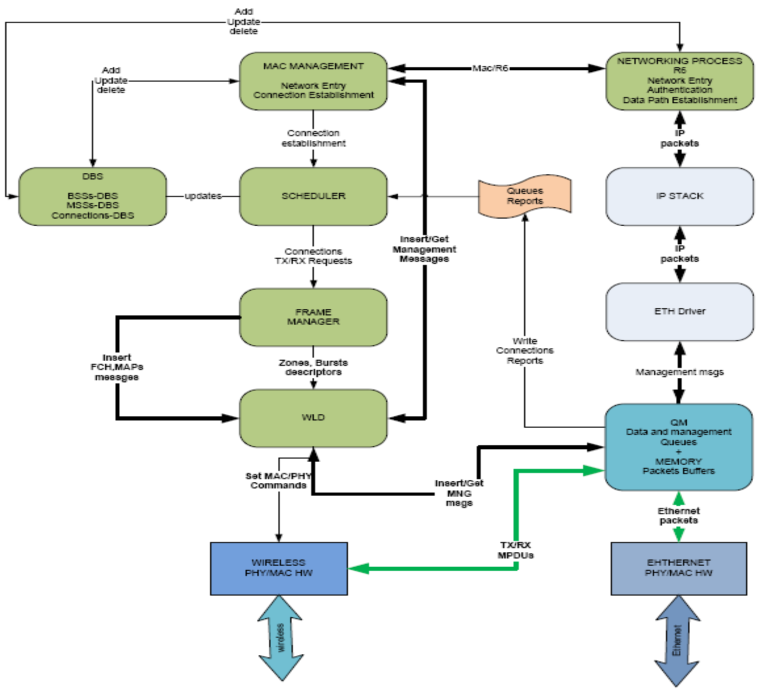

Fig. 4. Data and Control Flow Diagram

for the design of relevant product. In the continuity of the present work, we discuss the SW architecture used. The data critical path is run by the HW and controlled by the Scheduler, the Frame Manager and the Wireless Driver. All other missions are performed by other tasks, which have lower priority. DFD is demonstrated by green arrows; CFD is demonstrated by the black thin arrows; management messages are demonstrated by black wide arrows.

4.1 Downlink Data Flow

In the *downlink data flow*, packets are received via the Ethernet (ETH) port and classified by the ETH Rx Parser, which delivers the received packets together with their CID to the Queue Manager (QM). The latter inserts them to the proper connections queues, according to the specified CIDs and updates connections' reports according to the report groups defined by the Scheduler. The Scheduler polls the connection reports (every frame), and defines how many bytes should be transmitted from each DL connection. The Scheduler builds a list of requests for the Frame Manager. The Frame Manager, for a certain time frame (i.e. each 5ms), tries to "satisfy" Scheduler's requests, and plans (and builds) segment zones and bursts that contain MPDUs (MAC Protocol Data Units) for each connection, according to the specified rate (modulation/FEC (Forward Error Correction) and SISO (single-input, single-output) / MIMO (multiple-input, multiple-output) definition). After filling the frame, the Frame Manager builds both the DL MAP (which describes the transmitted bursts and the zones in the frame) and the UL MAP (which contains the Tx allocations for the MSs). The Frame Manager creates Tx commands for each transmitted MPDU; it builds Tx burst descriptors and zone descriptors and it delivers them to the WLD. The WLD sets the zone descriptors and the PHY descriptors to the PHY, and sets the Tx commands of each MPDU to the QM.

4.2 Uplink Data Flow

In the *uplink data flow*, for every frame, the Scheduler polls the bandwidth requests (as sent by the MSs) and other QoS UL connection attributes, and defines how many bytes are granted for each MS, for each UL connection. The Scheduler builds a list of UL requests to the Frame Manager. The letter, for the prescribed time of frame, tries again to "satisfy" Scheduler's requests, by using a method identical to the previous DL-related case. After filling the UL subframe, the Frame Manager builds the UL MAP; this describes the UL allocations and the zones in the UL subframe. The Frame Manager builds Rx burst descriptors and zone descriptors and delivers them to the WLD. According to the UL MAP, the MSs transmit their MPDUs, as per their UL Tx allocations. The WLD sets the UL zone descriptors and the Rx burst descriptors to the PHY. The PHY/MAC layer receives the UL mobile subscriber station transmission bursts in the allocated buffers memory. The hardware MAC extracts MPDUs from the received bursts into MPDU buffers, and inserts the MPDU buffers into the connection queues. The QM updates the report lists according to the received messages. The Scheduler reads the reports and updates the WLD about the received messages. The WLD then gets the received management messages and informs the MAC management about the management messages. The MAC handles the received management MPDUs and the QM inserts the user data traffic into the data user connection queues and creates report lists. Finally, the Scheduler reads the reports and orders the WLD to transmit the MPDUs to the Ethernet port, according to predefined directions for each queue.

5 Conclusion

Relay technology has focused significant attention due to several important and quite identifiable reasons i.e., simplicity, flexibility, deployment efficiency and cost effectiveness, as relays can permit a faster network rollout. Conformant to the scope of the European REWIND Research Project aiming to develop an effective relay station implementation for WiMAX technology, we have discussed several architecture principles and benefits for relay-based networks and then we have presented an essential description of the related RS software architecture design (PHY and MAC layers architecture) for the realization of a proper relay node required for the relay station functionality. Our approach has been based on the core concept of the Multi-Hop relay network architecture, conformant to the IEEE 802.16j standard.

Acknowledgments. The present work has been performed in the scope of the *REWIND* ("*RElay based WIireless Network and StandarD*") European Research Project and has been supported by the Commission of the European Communities - *Information Society and Media Directorate General* (FP7, Collaborative Project, *ICT-The Network of the Future*, Grant Agreement No.216751).

References

1. Tse, D., Viswanath, P.: Fundamentals of Wireless Communication. Cambridge Press (2005)
2. Rappaport, T.S.: Wireless Communications: Principles and Practice, 2nd edn. Prentice Hall, Upper Saddle River (2002)
3. Pabst, R., Walke, B., Schultz, D.C., et al.: Relay-Based Deployment Concepts for Wireless and Mobile Broadband Radio. IEEE Communications Magazine 42(9), 80–89 (2004)
4. Yu, Y., Murphy, S., Murphy, L.: Planning Base Station and Relay Station Locations, in IEEE 802.16j Multi-hop Relay Networks. In: IEEE International Conference on Communications (ICC), pp. 2586–2591. IEEE Press, New York (2008)
5. Hoymann, C., Klagges, K., Schinnenburg, M.: Multihop Communication in Relay Enhanced IEEE 802.16 Networks. In: 17th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Helsinki, Finland (2006)
6. Soldani, D., Dixit, S.: Wireless Relays for Broadband Access. IEEE Communications Magazine, 58–66 (2008)
7. Organization for Economic Coordination and Development (OECD): The Implications of WiMAX for Competition and Regulation (JT03204793). OECD, Paris (2006)
8. Walke, B., Wijaya, H., Schultz, D.: Layer 2 Relays in Cellular Mobile Radio Networks. In: IEEE VTC-2006 Spring, Melbourne, Australia (2006)
9. Van Nee, R., Prasad, R.: OFDM for Wireless Multimedia Communications. Artech House (2000)
10. Tucker, E.: Can Voice be the Killer App for WiMAX? The Basestation e-Newsletter, Aperto Networks (November 2006), `http://www.openbasestation.org/Newsletters/November2006/Aperto.htm`
11. Syputa, R.: The Impact of Mobile Multi-Hop Relay on WiMAX: Above and Beyond. Maravedis Newsletter 2(2) (November 7, 2007), `http://www.maravedis-bwa.com/article-32.html`
12. Andrews, J.G., Ghosh, A., Muhamed, R.: Fundamental of WiMAX - Understanding Broadband Wireless Networking. Prentice Hall, Englewood Cliffs (2007)
13. IEEE 802.16-2004: IEEE Standard for Local and Metropolitan Area Networks. Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems (2004), `http://standards.ieee.org/getieee802/download/802.16e-2005.pdf`
14. Nakamura, M., et al.: Standardization Activities for Mobile WiMAX. Fujitsu Sci. Tech. J. 44(3), 285–291 (2008)
15. Lin, B., Ho, P.-H., Xie, L.-L., Shen, X.: Optimal relay station placement in IEEE 802.16j networks. In: The 2007 International Conference on Wireless Communications and Mobile Computing (IWCMC 2007), Honolulu, Hawaii, pp. 25–30 (2007)
16. Zeng, H., Zhu, C.: System-Level Modeling and Performance Evaluation of 802.16j Multi-Hop Relay Systems. In: IWCMC, Next Generation Mobile Networks Symposium (2008)
17. Okuda, M., Zhu, C., Viorel, D.: Multihop Relay Extension for WiMAX Networks - Overview and Benefits of IEEE 802.16j Standard. Fujitsu Sci. Tech. J. 44(3), 292–302 (2008)
18. Chokhani, S., Ford, W.: Internet X.509 Public Key Infrastructure: Certificate Policy and Certification Practices Framework (RFC 2527). Internet Engineering Task Force (IETF), Sterling, VA (1999)