Networking for Communications Challenged Communities:
Architecture, Test Beds and Innovative Alliances
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D6.3 N4C
Mesh Networking for static long distance wireless sensor networks.

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ABSTRACT (Max 400 word)

Starting in May 2008, N4C is a 36 month research project in the Seventh Framework Programme (www.cordis.lu/fp7). In cooperation between users in northern Sweden and Kočevje region in Slovenian mountain and partners, the project will design and experiment with an architecture, infrastructure and applications in field trials and build two test beds.

This document gathers the results obtained during 2008-2009 concerning WP6 of N4C project. This is, first, a presentation of the modifications needed in order to add mesh capabilities to the WiMAX standard, and secondly introduces what could be an optimal routing/multihop strategy when using WiMAX to build a static long distance wireless sensor network.

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EXECUTIVE SUMMARY

The main objective of the N4C project is to extend pervasive, ubiquitous communications to currently communications-challenged communities (CCC's). These communities are remote rural areas where broadband access is not available.

According to this, the project pretends not only that the already existing applications will "just work" (once the technology is available) in these extended milieus, but also to refine the understanding of the needs of such applications and their users and to ensure that the technology will allow them to work in a more constrained environment.

Furthermore, it is also important concerning to the applications of the technology, to explore how the extension of the network into communications-challenged areas can be used to support appropriate novel applications.

One of the novel applications suggested is the remote sensing for meteorological and environmental monitoring, among other purposes, to support long term need of weather monitoring in areas where data collection is currently intermittent or non-existent. There is a need to collect environmental data from all regions of the globe to monitor the longer term effects on the global climate.

This document presents the studies and solutions for what could be a network of meteorological stations with several sensors, based in a static ad-hoc scenario using WiMAX technology.

The first chapter of this document analyzes the traditional characteristics of mesh networking, and its application to sensor networks.

In the second chapter, we study the WiMAX standard focusing in the main features affected by an ad-hoc operation: operating differences between working as Base Station (BS) or Subscriber Station (SS).

After that, in the next three chapters we study the constraints of our particular scenario, and keeping those constraints in mind, the needed modifications on WiMAX standard PtMP equipment to accomplish a proper and feasible mesh node in this meteorological sensors network. Also, we introduce the "ad-hoc network organizer", as a generic entity (a DTN device, for example) that needs to fulfill certain features regarding routing and multihop strategies, and communication with the WiMAX mesh node.

Finally, in Chapter 6 we present a use case of configuration and operation of a small network with four mesh nodes and their correspondent sensors.

0. ACRONYMS

ATDD	Adaptive TDD
BS	Base Station
BW	Band Width
CCR	Communications Challenged Regions
CGI	Common gateway interface
CINR	Carrier to Interference-plus-Noise Ratio (in dBs)
CPE	Customer premises equipment
DL	Downlink
DPC	Data processing centre
DTN	Delay Tolerant Network
IP	Internet Protocol
LAN	Local area network
SS	Subscriber station
TDD	Time division duplexing
UGS	Unsolicited Grant Service
UL	Uplink
WiFI	Wireless Fidelity (IEEE 802.11)
WiMAX	Wireless Interoperability for Microwave Access (IEEE 802.16)
XML	Extended Markup Language
XML-RPC	XML Remote Procedure Call protocol

1. WIRELESS MESH NETWORKS AND WIRELESS SENSOR NETWORKS.

In this chapter we will give some background of what is commonly understood as wireless sensor networks, mesh networking and specifically wireless mesh networks.

We will see that the most generic wireless sensor networks bring a large amount of restrictions that we do not need to keep in mind for the consecution of our project, which simplifies aspects such as power supply and mobility of nodes.

Finally in the chapter, we try to synthesize the main requirements a wireless technology need to have in order to be able to give support to a wireless mesh network. With this, we begin to introduce some of the necessary modifications we need to do on WiMAX PtMP technology to be able to serve as infrastructure of a wireless mesh network.

1.1 WIRELESS SENSOR NETWORKS.

1.1.1 General description.

A wireless sensor network consists of spatially distributed autonomous sensors to cooperatively monitor physical or environmental conditions.

Each node in a sensor network must have, besides the proper sensor or sensors, the required technology to transmit the sensor information, this is, a radio transceiver or any other wireless communication device.

A sensor network normally constitutes a wireless ad-hoc network.

The main characteristics of a wireless sensor network include:

- Limited power that sensor can harvest or store.
- Ability to withstand harsh environmental conditions.
- Ability to cope with node failures.
- Mobility of nodes.
- Dynamic network topology.
- Tolerant to communications failures.
- Heterogeneity of nodes.
- Large scale of deployment.
- Unattended operation.
- Node capacity is scalable, only limited by bandwidth of gateway node.

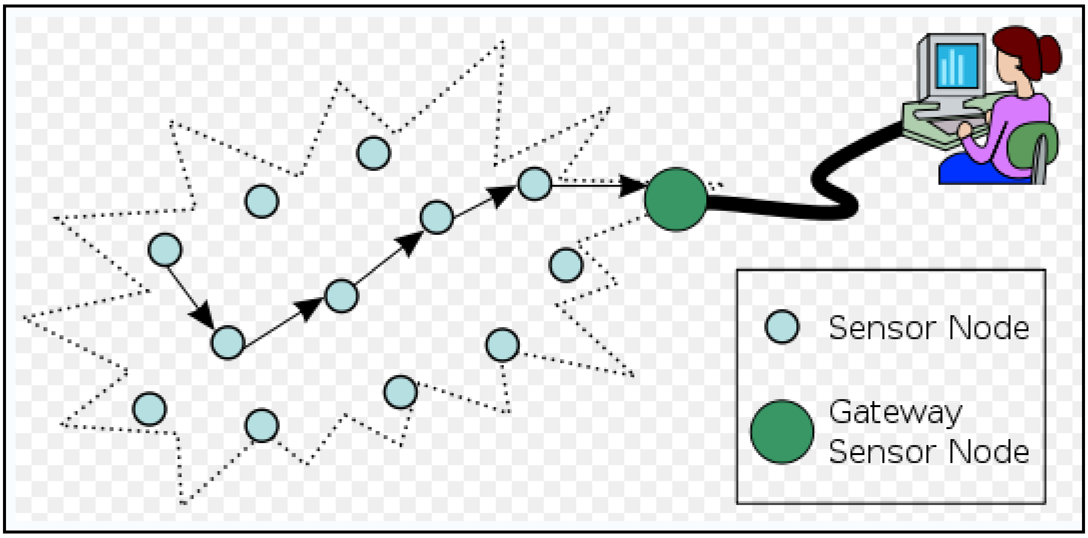

Figure 1-1: Classic sensor network.

1.1.2 N4C Fixed Sensor Network. Climate data gathering.

The scenario proposed in this project is a network of meteorological stations with several sensors to evaluate climate and other weather parameters.

Several simplifications can be made when comparing the required sensor network to the most general sensor network described above.

First of all, we consider our climate data gathering network as a static and fixed network, where topology is known. Therefore we don't need to give support to a proper ad-hoc wireless network, where nodes are mobile and they build a topology that is constantly changing, and consequently a proper dynamic routing algorithm is needed.

Concerning the rest of characteristics, comments on the specific application we are considering are added below:

- *Limited power that sensor can harvest or store.* In our scenario, the stations are equipped with batteries for power supply.
- *Ability to withstand harsh environmental conditions.* The real scenario may have sensors placed in locations with very harsh environmental conditions, but this concern is out of the scope of this deliverable.
- *Ability to cope with node failures.* The mesh topology assumed will give redundancy to the network.
- *Mobility of nodes.* No need to consider this restriction since nodes will be static.
- *Dynamic network topology.* No need to consider this restriction since network will be static.
- *Tolerant to communications failures.* Being a static topology, communication failure will be rare. Nevertheless, nodes would have to be able to detect lost links to their neighbours so communication can be established through alternative paths.

- *Heterogeneity of nodes.* Nodes will be homogeneous.
- *Large scale of deployment.*
- *Unattended operation.*
- *Node capacity is scalable, only limited by bandwidth of gateway node.*

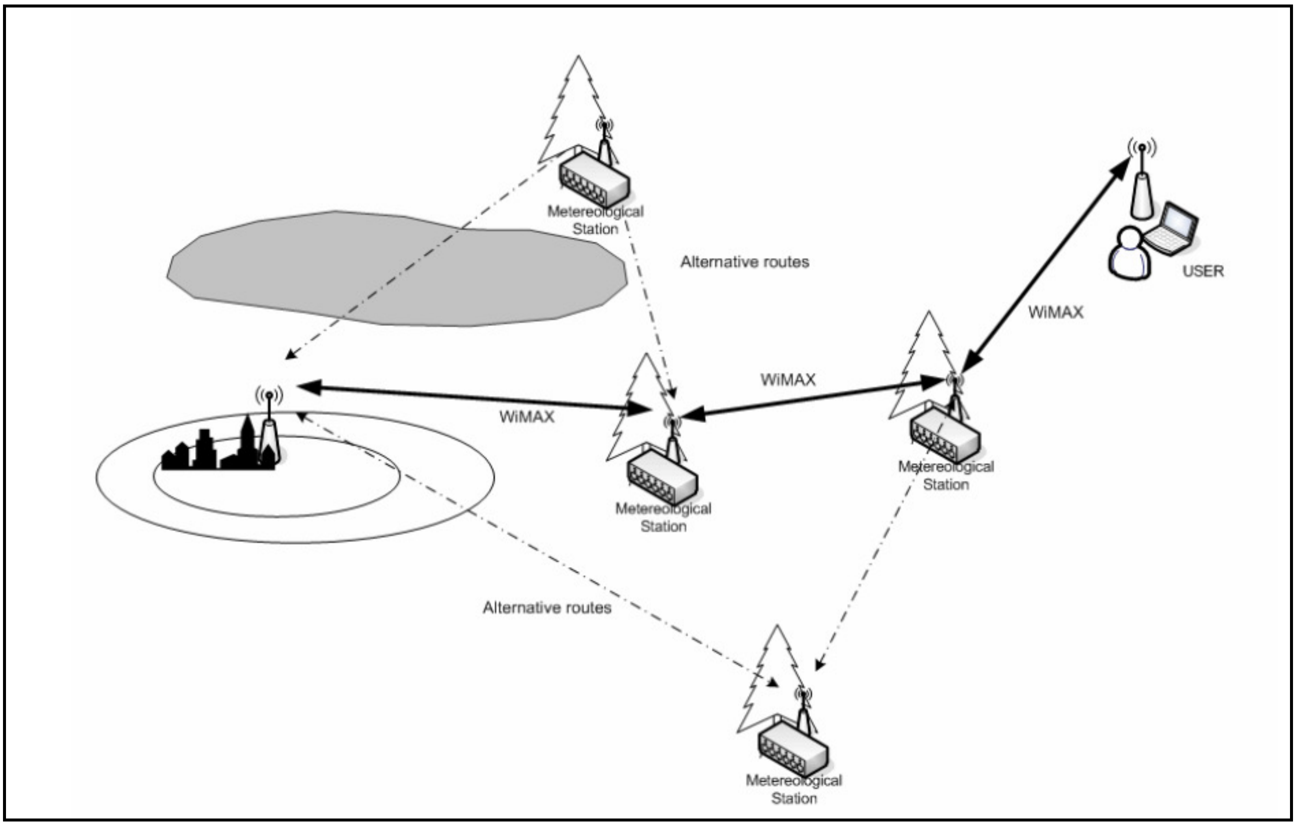

Figure 1-2: N4C mesh sensor network

1.2 MESH NETWORKING AND WIRELESS MESH NETWORKS.

1.2.1 General description

A mesh network is a local area network where each node acts as an independent router. The main characteristics of mesh networks and mesh networking are:

- Nodes are connected to each other building a redundant topology: if a node can no longer operate, the others can still communicate with each other, directly or through intermediate nodes because there is often more than one path between a source and a destination in the network.
- When all the nodes are directly connected to each other, we are talking about a full mesh topology. In case connections between nodes are not always direct, we refer to a partial mesh topology.

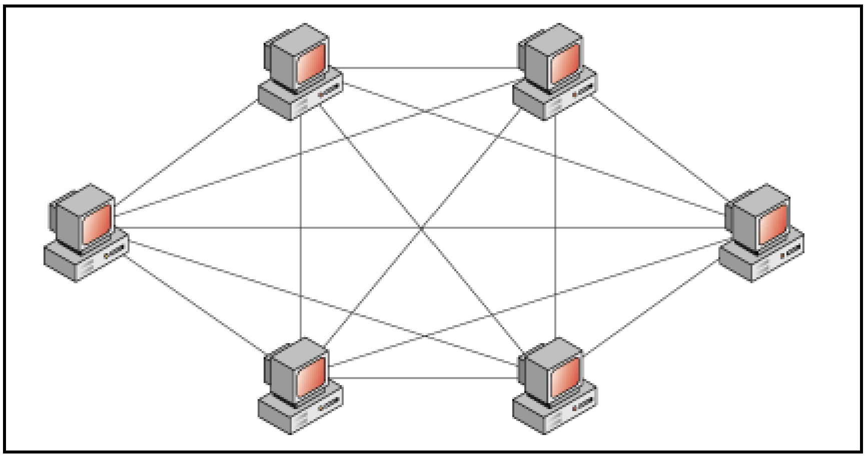

Figure 1-3: Full mesh topology.

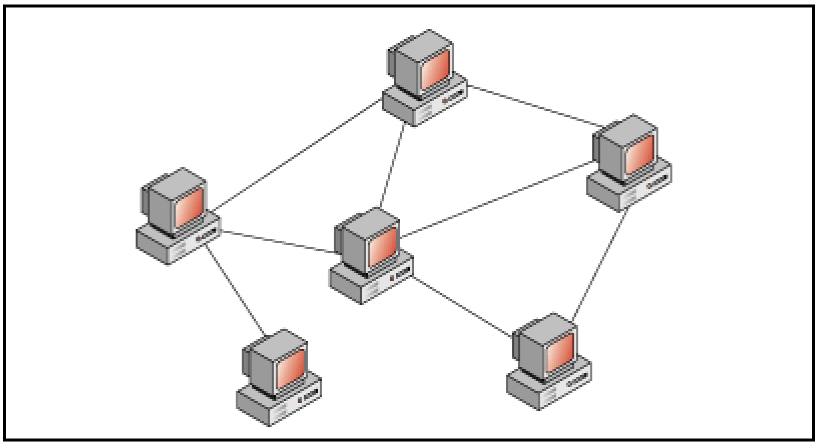

Figure 1-4: Partial mesh topology.

1.2.2 Wireless mesh networks – advantages and disadvantages of a wireless topology.

Wireless mesh networks are the most typical application of mesh architectures. A wireless mesh network is made up of radio nodes organized in a mesh topology.

A wireless mesh network includes advantages coming from its wireless nature:

- The architecture of a wireless mesh network is the same architecture that has a router network, minus the cabling between nodes. The mesh architecture sustains signal strength by breaking long distance into a series of shorter hops.
- Wireless mesh architecture will be able to provide a high aggregated bandwidth within the specific cover area.
- We can think of three types of wireless mesh networks:
  - Infrastructure wireless mesh networks, where mesh routers form an infrastructure to be used by the clients.

    - Client wireless mesh networks, where client nodes constitute the actual network and they are in charge of performing routing and configuration tasks.
    - Hybrid wireless mesh networks, where mesh clients can perform mesh functions as well as accessing the network.

- Usually, in wireless mesh networks we can talk about a stable topology.
- Concerning to traffic, this usually goes from/to a gateway or traffic drain, and not so much between clients.

On the other side, the wireless nature of a mesh topology may bring some challenges and constraints to communication:

- Dynamic routing algorithms and protocols.
  Deciding over the best path is not trivial when dealing with mesh networks. Usually, the best path decision will rely in a distributed and adaptive logic, where every node in the network is responsible of maintaining its routing table updated with information coming from two sources: its own data base (containing information of the network topology - static), and the information resulting from the protocol execution.
  Dynamic routing protocols make their distance measurements over a certain metric or criteria. When dealing with wireless networks, this metric must be based on the link status with their neighbors. At this point we come up with the first difficulty derived from the wireless nature of the links. It is not trivial to evaluate the link quality with a neighbor from a single measurement. For example, focusing in WiMAX, the link quality can be measured from the CINR of the link, but, during how long? Quality of radio links is attached to a great amount of factors that may vary from one minute to the other, and making assumptions about the link quality from a single measurement from a link that was just established may not be a very reliable metric, even though there isn't really any other.

- Another restriction that we encounter from the fact that we deal with a wireless network is that the predictability and reliability of the link may not be the expected during a transmission. As we mentioned, link quality is attached to several statistic factors and its behavior is unpredictable in a short period of time.

- Concerning to this particular case where the selected technology is WiMAX, we cannot count on the standard specification to establish the guidelines in the management of the spectrum or transmission scheduling. Previous versions of the IEEE 802.16 specification did contemplate a mesh operation, but it got discarded in the definitive version of the standard.

- Concerning to bandwidth, when calculating the aggregated throughput of the covered area we may have good ratios or estimations. In contrast, during operation we may encounter several difficulties that decrease throughput notably: delay in the link establishment, primary paths are unavailable or busy and the secondary paths operate in modulations that cannot give the same performance, external conditions that force the nodes to operate in more conservative conditions…

1.2.3 Wireless mesh networks: requirements of the supporting technology.

Wireless mesh networks can be implemented with various wireless technologies including 802.11, 802.16, cellular technologies or combinations of various types.

Mesh networks as well as ad-hoc networks, have a decentralized nature. We already mentioned how every node in the network must operate as an independent router. When referring to wired networks, this means that mesh networks cannot rely in a pre-existing infrastructure of routers.

In wireless mesh networks, more specifically those implemented over 802.11 or 802.16 technologies, the fact that a node must be able to operate as an independent router means that, according to topology, the redundancy of the network, the load of the network, or any other possible factors, the node must be able to operate in any of the two roles (or logical entities) – master/slave - of a managed (infrastructure) wireless network.

Due to the distances planned for the weather sensor network of this project, the technology chosen for this scenario is WiMAX. So, focusing in WiMAX, the mesh node will have to be able to operate indistinctly as any of its two operation modes (BS/SS) according to the needs of the routing.

In the following example we can see how information goes from node 3 to node 4 in T1, taking the first hop, and from node 4 to the DPC in T2, taking the second hop.

If we focus in node 4, during the first hop, it needs to act as BS. It will also have a certain radio configuration to be able to communicate with node 3, and it is also needed to establish an uplink flow service.

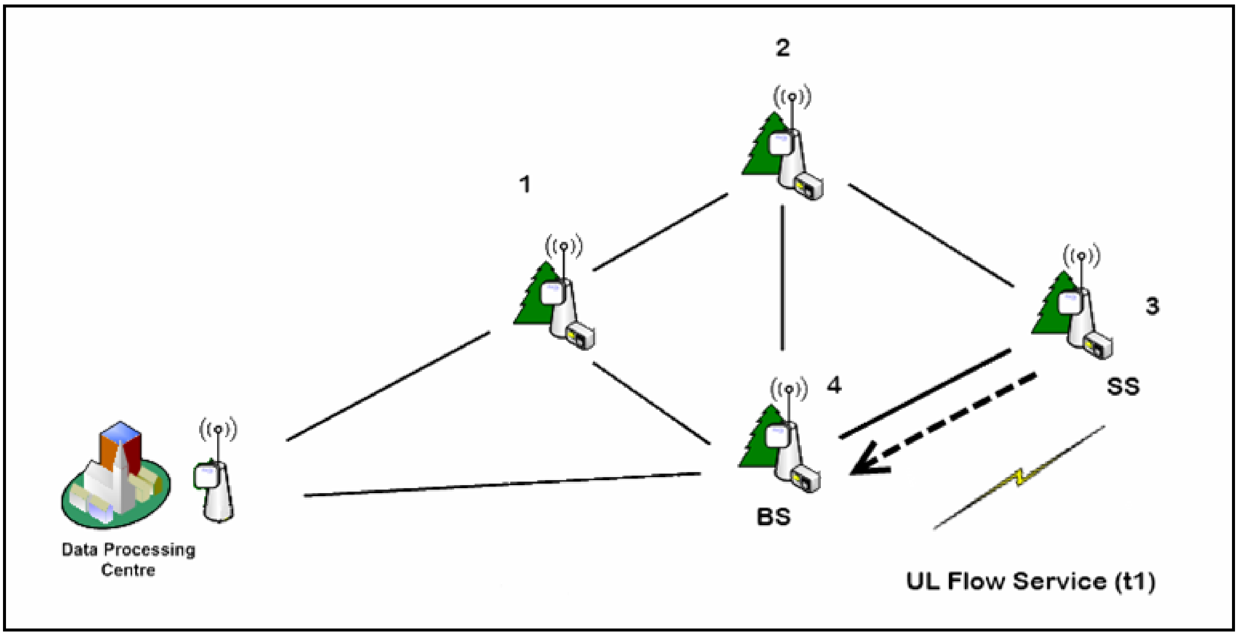

Figure 1-5: 1st hop.

In contrast, during the second hop, node 4 needs to operate as SS with its BS placed in the DPC. A different radio configuration for this link will be set, and this time the BS in the DPC will create another uplink flow service to bring information from node 4.

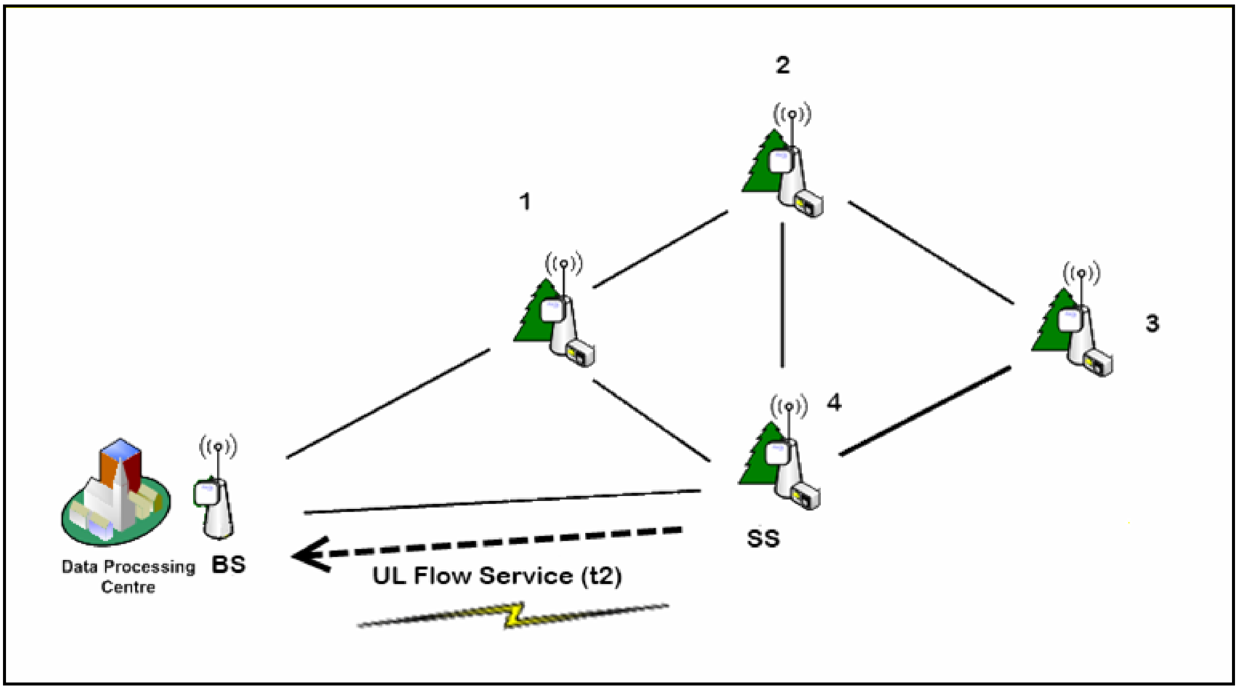

Figure 1-6: 2nd hop.

2. 802.16 WIMAX OPERATION MODES

The IEEE 802.16 system architecture consists on two logical entities, the BS and SS. Both the BS and the SS have instances of the IEEE 802.16 MAC layer and PHY layer, in addition to other support functions. However, specific functions performed by the MAC or PHY differ depending whether it is a BS or a SS, and the standard defines the BS and SS specific behavior in detail. In PtMP networks, the BS and SS are in a *master-slave* relationship, where the SS must obey all medium access rules enforced by the BS. The SS in some configurations is referred to as the *customer premises equipment* (CPE) when the SS (or any part of it) is physically located within the customer's premises.

When comparing and understanding the two modes of operation, we will see that there is a great asymmetry in the complexity of each of them. The SS is intended to be much simpler equipment with fewer requirements concerning performance, accuracy, and complexity of the operation logic.

In this chapter, we will cover the main functions of these two logical entities.

2.1 MODE BASE STATION (BS).

In summary, the BS is responsible for the following functions:

- The main function of a BS is to route (or bridge) the traffic from and to the network. In a PtMP topology, we need to know that traffic doesn't flow from SS_A to SS_B, but it goes from SS_A to BS and from BS to SS_B. This implies a large amount of traffic processing.
- Enforcing MAC and PHY parameters: it concerns to the BS to set the most part of the radio parameters (transmission power, attenuation, frame duration, channel frequency, UL/DL modulation in case it is forced).
- BS scheduling tasks: performing bandwidth allocation for DL (per connection) and UL traffic (per SS) and performing centralized QoS scheduling, based in the QoS/service parameters configured by the provisioning module and the active bandwidth request (BW requests) received from the SS
- Communicating the per-frame schedule to all SSs and supporting other data and management broadcast and multicast services.
- Transmitting/receiving data and control information to/from one or more SSs within the same frame: periodic ranging, services creation/deletion messages, polling…
- Performing connection admissions control and other connection management functions.
- Providing other SS support services such as ranging, clock synchronization, power control and handoff.

2.2 MODE SUBSCRIBER STATION (SS).

The SS is responsible of the following functions:

- Identifying the BS, acquiring PHY synchronization, obtaining MAC parameters, and joining the network if necessary.

- Establishing basic connectivity, setting up additional data and management connections, and negotiating any optional parameters as needed.
- Generating BW requests for connections that require such requests to be generated, based on the connection profiles and traffic
- Receiving broadcast/multicast PDUs and unicast PDUs and forwarding them to the appropriate modules.
- Making local scheduling decisions based on the current demand and history of BW requests/grants, when a BS allocates bandwidth for the SS.
- Transmitting only when instructed by the BS to do so or the SS has some information that qualifies for transmission in one of the slots that may cause "contention" (e.g., ranging and BW requests in contention or broadcast allocations)
- Unless in sleep mode, receiving all schedule and channel information broadcast by the BS and obeying all medium access rules, transmitting data only when the BS allocates slots
- Performing initial ranging, maintenance ranging, power control, and other housekeeping functions.

One of the basic differences between the BS and the SS in a PtMP configuration is that the BS, which acts as a centralized controller and a centralized distribution/aggregation point, has to coordinate transmissions to/from multiple SSs, whereas the SS need to deal with only a BS. All traffic originating from an SS, including all SS-to-SS traffic must go through the BS. Therefore, in a typical IEEE 802.16 system, the BS has to have additional processing and buffering capability (compared to typical SS) to support a reasonable number of SSs.

2.3 CONCLUSIONS CONCERNING TO MESH.

The fact that a node inside a WiMAX network needs to change from operating as a BS to operate as a SS (or vice versa), has the following implications:

2.3.1 Changing from BS to SS.

In the case the change is from BS to SS, the new node SS needs to make link with a BS. In order to do this, the SS needs to scan de media and synchronize to the DL.

This scanning process may occur in two different ways:

- The equipment now acting as SS is aware somehow (out of scope) of the most probable neighbour BSs and their radio parameters. In this case, the SS will try to synchronize to these BSs. Besides knowing the physical parameters that make the link possible, a proper ID verification of the BS will be needed to make sure the node enters in the mesh covered area.
- A more flexible configuration will consist in a proper media scanning. In this case, the SS will start trying the detection of a BS going through all the possible channel frequencies, channel BWs, and cyclic prefixes. In this case, the SS will make link with the first BS detected. Additional identification could be included here too.

In this case, previous configuration is not needed (besides the BS identification), but the initial ranging process will start later since the scanning of the media may take several minutes depending of the configuration parameters of the nearest BS.

The scanning process will end with the SS synchronized to the DL initial preamble and frame description header (FCH) that gives the information about the rest of the frame (Downlink/Uplink Channel Descriptor). With this, initial ranging will start and after the capabilities negotiation, service flows will be created and data transmission will be possible.

2.3.2 Changing from SS to BS

In case the change is from SS to BS, it will be necessary that the equipment performing as BS has somehow all the information to build and to start transmitting the DL frame. This implies in the first place, to be aware of the entire physical configuration: channel frequency, frame duration, channel bandwidth (BW), cyclic prefix, limits on DL/UL modulation (if any), transmission power and attenuation in reception.

In the second place, the equipment performing as BS needs to have provisioned all the possible users that may establish link with it, so once the ranging phase is covered, flow services can be built and consequently data throughput can start. Concerning to this, we consider the possibility of provisioning groups of users, so any of the neighbours that are allowed making link with the new BS, create the same flow services.

Finally, the equipment performing now as BS will have to be able to schedule the user's flow services according to its QoS and the BW requests the users may send.

3. N4C SCENARIO: MESH NETWORKING FOR STATIC LONG DISTANCE WIRELESS SENSOR NETWORKS.

In this chapter we will define the characteristics that a mesh node that belongs to the mesh network of the N4C scenario should have.

We will consider the mesh node as an entity that includes the proper WiMAX technology for communications, and also additional logic that may be implemented by the meteorological station, or an ad-hoc network entity such as a DTN device, or a generic "mesh NW organizer element".

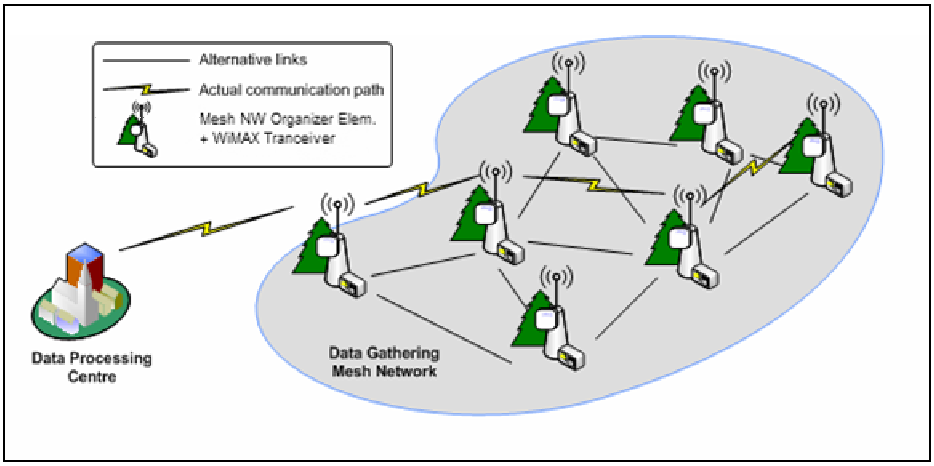

Figure 3-1: N4C scenario.

3.1 SCENARIO ASUMTIONS AND OTHER CONSIDERATIONS.

These are the assumptions and constraints assumed in the project:

- Information will flow from each of the mesh nodes to a data processing centre (DPC). Data throughput between nodes is not contemplated, therefore the information any node must have regarding to routing is all the possible "next-hop neighbours" in the path of the DPC.
- All mesh nodes in the network are homogeneous in the sense that are all both hybrid wireless mesh nodes (mesh clients can perform mesh functions as well as accessing the network).
- We consider mesh network static. These means that, even though certain redundancy is assure, given a particular node, all its neighbours will remain the same over time and the possible paths to the DPC are previously known.
- The mesh network is delay tolerant. Long latencies are permitted and the network is tolerant to communications failures.
- Communication is contemplated as a chain of asynchronous hops between two mesh nodes. In every hop a WiMAX link is established between a mesh node BS and a mesh node SS. WiMAX flow services are created and information goes from source to destiny. Once information gets to the mesh node destiny, it is stored in the node until the next hop is ready, this is, link with the next node is established and ready to process traffic. And so forth until arriving to the DPC.

- Every mesh node has the necessary information to establish the WiMAX link to the proper neighbour in order to take the next hop in the path to the DPC. This information, as we described previously, includes physical distance to the next node, radio parameters and operation mode (BS/SS). The generic entity "mesh NW organizer" will be in charge of providing this information to the WiMAX transceiver which will be able to understand it and apply it.
- In the nodes where redundancy (multi-path) is available, every mesh node will incorporate the logic to assume that a WiMAX link with the optimal neighbour is not possible, and a secondary link needs to be established.

4. MESH OPERATING MODE BROUGHT TO WIMAX.

As it has been previously introduced, one of the main challenges of using standard 802.16 PtMP equipment in a Mesh scenario is that the equipment itself must have the ability of changing its behavioral mode.

This part of the document describes the integration of this functionality in working standard equipment from Albentia Systems.

4.1 OVERVIEW

The following figure shows the general high-level block diagram of the complete WiMAX systems, both in BS and is SS alternatives:

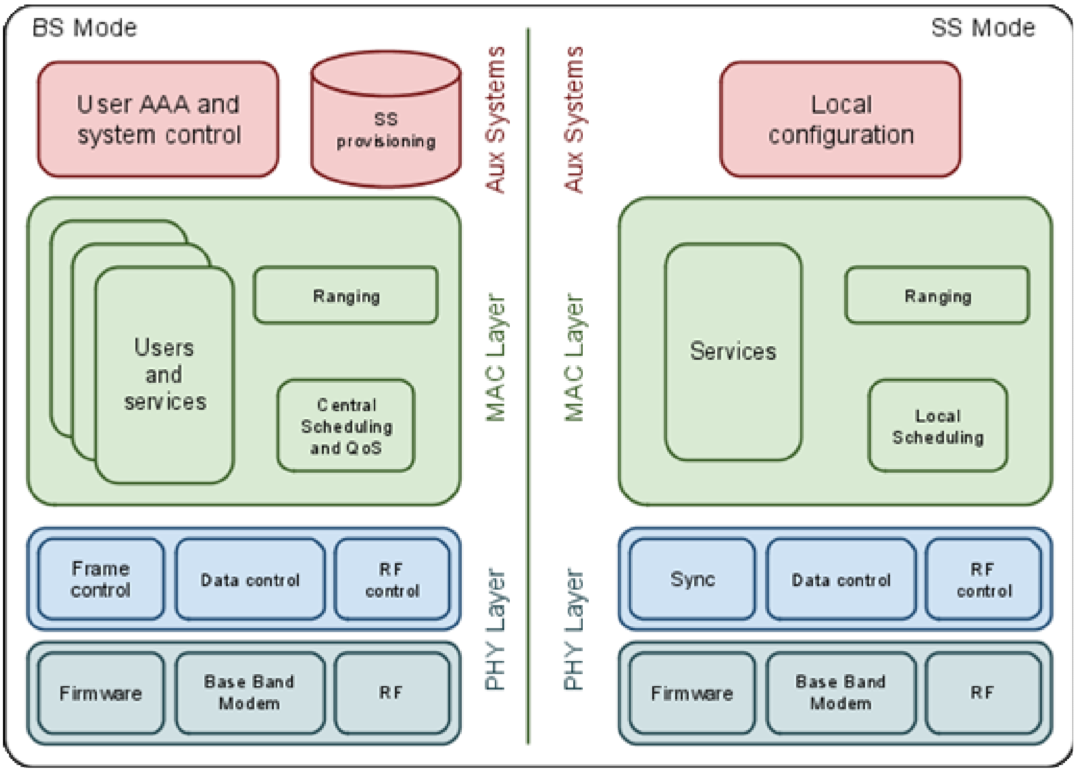

Figure 4-1: BS/SS WiMAX System

In this picture the main component differences between the BS and the SS are depicted. As it has already been explained, the BS is in charge of managing the full frame, enforcing frame parameters and is the key for the service management and QoS guarantee. The BS also holds a relationship of 1-n with the connected SSs, meaning that the BS must take care of many users at the same time, tracking all their needs, their signal qualities and allocating traffic both in the downlink and in the uplink for all of them. To do so, the BS has some main architectural components:

- PHY Layer: it is divided in two sub layers, the lower one implemented directly in the hardware and the firmware, and the higher one being a piece of software.

- HW PHY: this part of the system modulates and demodulates the WiMAX signal, generating the RF signal and controlling all the subsystems of the HW: clocking circuits, CRC calculations...
- SW PHY: this part of the system is a HAL (hardware abstraction layer) for the higher layer, and also has the responsibility to control all the functionality provided by the HW PHY: configuration of the board, interruptions handling, frame management as indicated by the MAC...

- MAC Layer: this is the main part of the system and where it is controlled from, as a real time process. Its main components are:
  - Central Scheduling: key component for the frame control and QoS tasks. On a frame by frame basis, it decides the allocation of slots in the DL and UL for all the users and for contention zones (ranging, BWreq...). It must take into account the needs from all the SS both in the DL and in the UL, and all the QoS admitted parameters for all the active services.
  - Ranging: this module takes care of the status of all users in terms of signal quality, timing control and modulation selection. It must also negotiate the network entry of the SSs and it is constantly communicating with the aux systems in the management layer.
  - Users and services: these are the representation of all the active users and their services at the BS. They take care of all of the traffic flow through the system: fragmentation, packing, PDU delimitation...
- Aux Systems: this is the higher management part of the system. It is in charge of the system high-level management and also implements the provisioning database and all of the interfaces for the management of the equipment.

The main differences between this implementation and the SS one are:

- PHY Layer:
  - HW PHY: the firmware at the SS must take care of the reception of the BS frame, which very different from the BS one, and also preprocess all the frame description messages.
  - SW PHY: the frame control at the SS is totally driven by the messages of the BS, and there is also the need for a synchronism module. This Sync Module takes care of getting and tracking the correct frame parameters from the BS.
- MAC: basically, the MAC implementation at the SS is designed to be very compact and efficient in terms of CPU power and behavior. It is only responsible for the local scheduling and one the management and traffic of its own services.
- Aux Systems: the SS does not have the need for the provisioning database, but it needs all the rest of the systems and the management interfaces.

4.2 INTEGRATION OF WIMAX OPERATING MODES IN THE SAME MAC LAYER.

The main problems and its solutions to integrate both modes into the same equipment, as the system itself, can be divided in different layers: PHY, MAC and Aux Systems. All these problems and solutions are detailed below.

Generally speaking, the design of the software of the equipment follows an Object Oriented pattern. This allows a high level of abstraction and, even at system kernel level, polymorphism behaviour. Taking this into account, the general problem of integrating two working modes into the same piece of software requires workload on the problem analysis side and then in the implementation time, but it does not imply deep modifications in the system architecture.

4.2.1 Integration of the PHY Layers

The following are the main problems that must be faced when trying to support both modes at the PHY level in the same piece of equipment:

- MODEM: the base band modem must be compatible with both modes. This is needed as the hardware to run the BS and the SS must be the same.
- Firmware: the firmware that gives support for the board and the modem must be aware of both modes. This is specially important because in BS mode the clock and frame control are done from the master point of view, whereas in SS mode, the system must sync and track to those of the BS.
- SW: the software must be aware of both modes and must be able to change as required.

To solve all of these issues, the following solutions have been implemented:

- The chipset currently in use in the Albentia Systems equipment has support for SS mode, so this is not a problem in the implementation of the mesh equipment.
- To integrate the needed functionality of the firmware:
    - A generalization of the functionality has been done, re-using all the code for both modes, reducing the overall complexity and improving the maintainability of the code.
    - The needed registers have been added, to allow the SW PHY layer to select the currently working mode.
    - All the registers of the BS and the SS that do not control the same or equivalent functionality have been remapped in an organized way. This allows the software to access the BS and SS registers in different memory positions.
    - With these changes, the total used resources of the programmable logic are still under the capabilities of the integrated chips.
- To integrate the needed functionality of the PHY software layer:
    - A general PHY object has been abstracted to isolate the behavior of both modes.

- Methods for mode change and retrieval has been added to the PHY object.
- The interface needed by the BS and SS mode has methods that can be shared and methods specific for the working mode. The shared methods have been generalized and the specific methods have been added, thus resulting in a full PHY interface valid for both BS and SS alternatives.

The following figure shows a conceptual view of the PHY object with full support for both BS and SS modes.

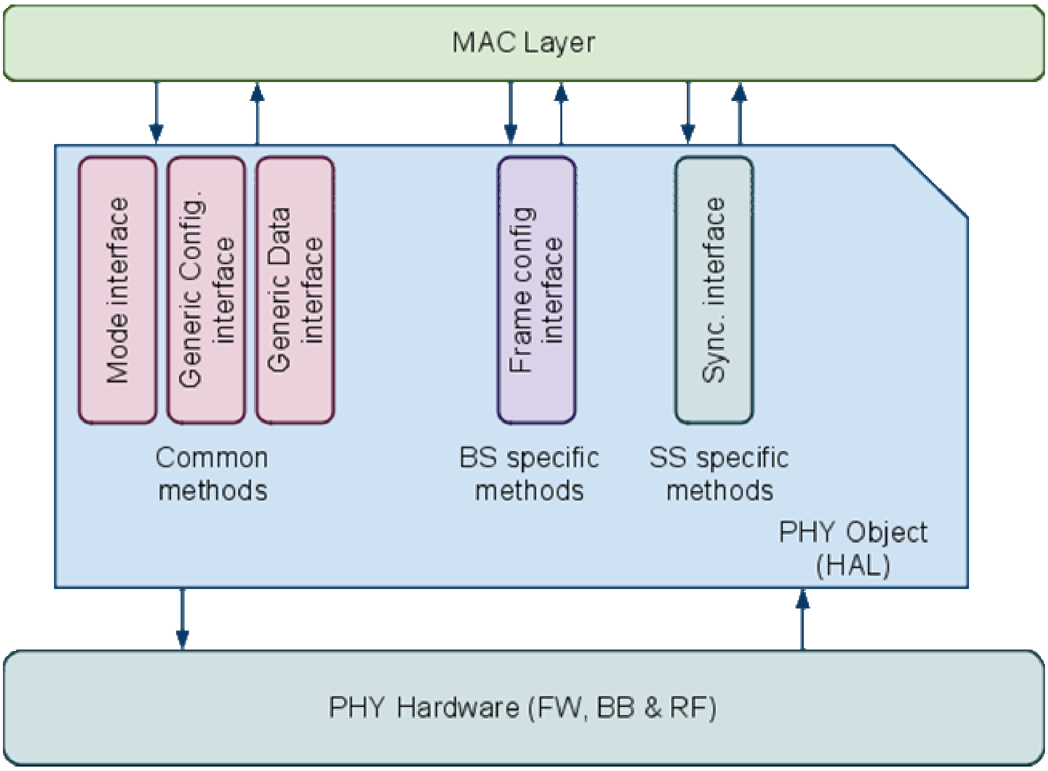

Figure 4-2: PHY Object for BS and SS.

4.3 INTEGRATION OF THE MAC LAYERS.

The problems that arise when integrating both versions of the MAC system is different, mainly because there is not hardware/firmware, but the complexity of the system is very much increased. The main issues that had to be solved here were:

- SW management: the software itself must provide functionality to manage both operation modes.
- SW integration: the behaviour of the MAC layer is totally different in the BS and SS mode, thus the networking and the management are also different.
- SW interfaces: the interfaces exposed to the higher management layer have very different functionalities depending if the equipment is operating in SS or in BS mode. The interface shown to the PHY layer has exactly the same problem.

- The CPU available power and total system memory must meet the requirements for both modes.

The solution for these problems is mainly based on the object oriented design of the system. The main implemented strategies have been:

- Generate a higher level MAC object that abstracts the methods and functionality for the MAC mode itself.
- Generate an abstracted Scheduler and Ranging Module that provide the same interface but implementing different behaviours, depending on the mode.
- Integrate the PHY interface, so that it exposes the common methods and all of the BS and SS specific functions.
- Generate a management object that allows the system to instantiate BS and SS MAC objects, and to handle them.
- The management interface has been expanded to include the SS and BS functionality for the Aux Systems.

The following picture shows the general approach and the modules that have been implemented:

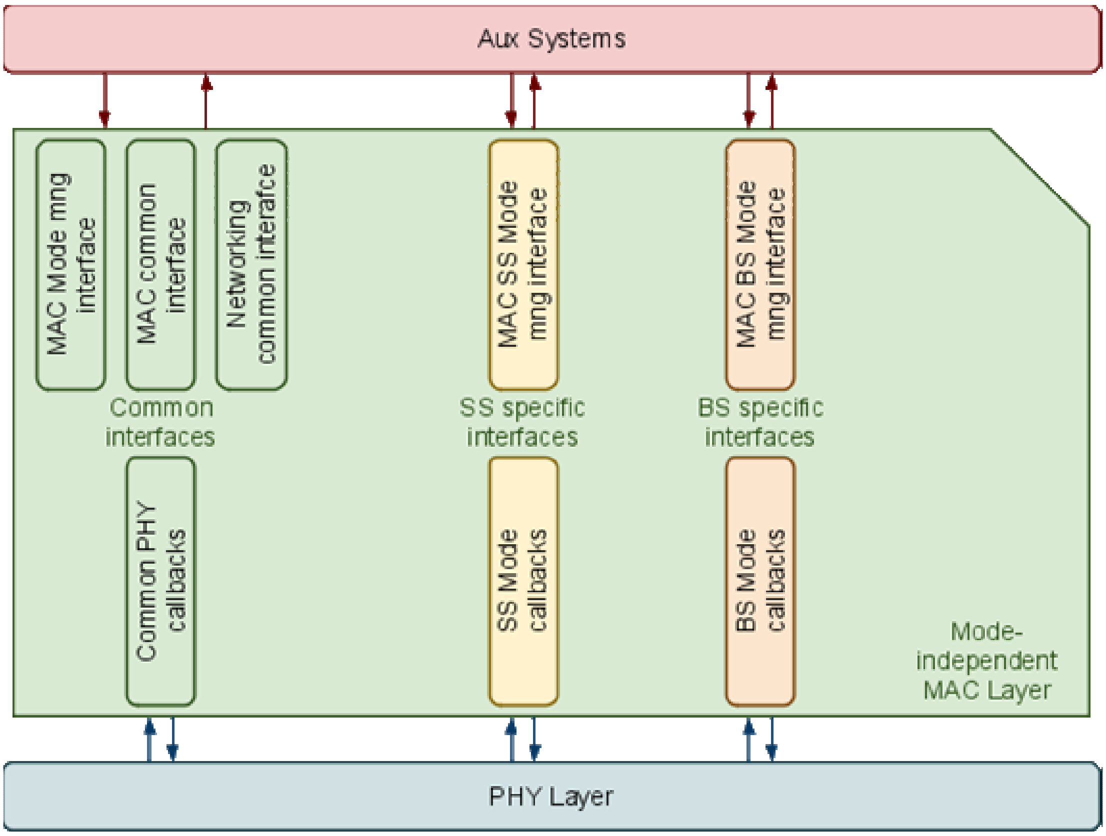

Figure 4-3: MAC Object for BS and SS.

4.4 INTEGRATION OF THE AUXILIARY SYSTEMS.

The Auxiliary Systems are all the pieces of software in the system in charge of the higher level management and system configuration. The integration of the working modes presented the main following problems:

- Provisioning: the AAA and provisioning system present in the BS equipment is not needed at all when working as an SS.
- Configuration files: the configuration parameters of both systems are totally different, and so they are the configuration files in which the information is stored.
- Events and management: the events and management functionality is different when working in BS and SS modes.

To solve these issues, the following solutions have been integrated in the system:

- Now, the provisioning system is aware of the system mode. It is internally and automatically disabled when the equipment changes to SS mode.
- The configuration has been generalized in a way that all the parameters, both common and specific are supported by the configuration software and by the configuration files. To do this, XML files have been used. XML structures have the ability to handle multiple parameters and to understand files even when some parameters are missing.
- The general management piece of software, also called "WiMAX daemon" now can handle both types of events and calls. To do so, the daemon knows in which working mode the system is, and acts correctly.

4.5 SWITCHING OPERATIONS.

With the system supporting both operational modes (BS and SS), the procedures for the equipment to change modes are defined in a way that any operator, directly or using an M2M interface such as XML-RPC, can successfully select and set-up any of the modes. It is **very important** to follow these procedures because they are designed to guarantee the correct configuration of the modes.

4.5.1 BS to SS mode switching

The following flow diagram shows the correct procedure to switch from BS to SS modes:

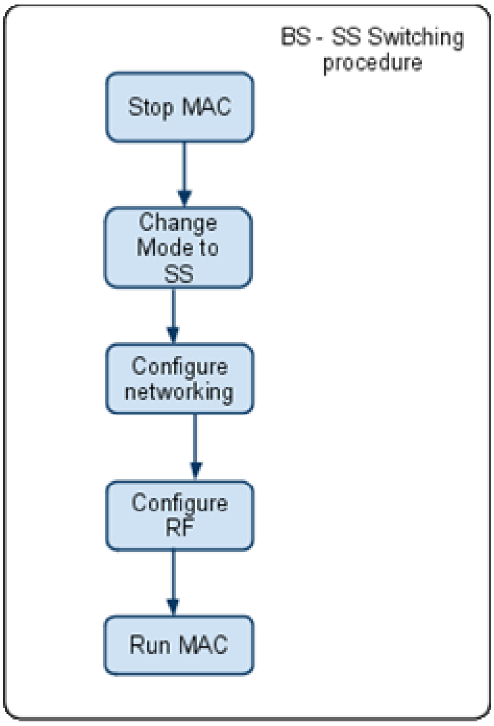

Figure 4-4: BS to SS mode switching.

4.5.2 SS to BS mode switching.

The following flow diagram shows the correct procedure to switch from SS to BS modes:

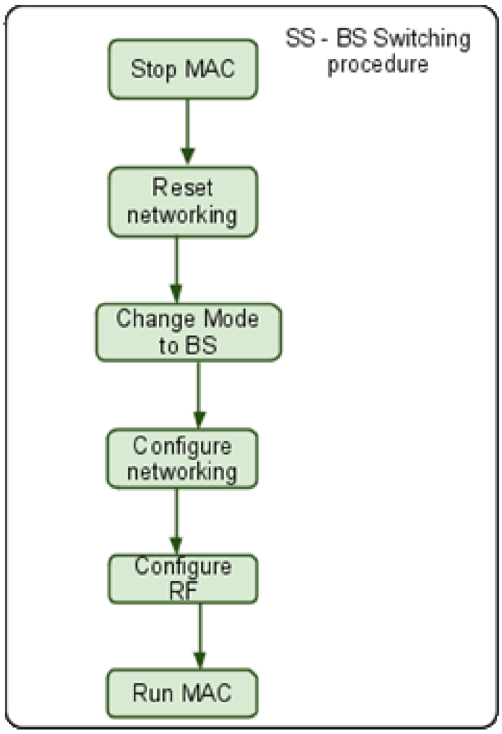

Figure 4-5: SS to BS mode switching.

5. DYNAMIC SWITCHING INFRASTRUCTURE

We already know how the WiMAX transceiver will be capable of switching from one mode of operation to other (BS to SS and vice versa). In this chapter we will describe the work done to give the WiMAX transceiver the ability to receive from an external entity the necessary commands to actually make this switch as well as other commands and calls. This necessary architecture is based in XML-RPC.

We will see that once the WiMAX equipment is adapted to receive remote commands, it acquires a great flexibility that makes it suitable for a long list of applications.

5.1 MAIN ESQUEMA: MESH NETWORK ORGANIZER ELEMENT.

The Mesh Network Organizer Element (MNOE) is a necessary entity that will have various tasks inside the mesh node:

- It will be in charge of the storage of the sensor information until the moment of its transmission. Therefore, communication or even integration with the proper weather sensor is necessary, but out of the scope of this deliverable.
- The MNOE is aware of the topology of the mesh network, and has the necessary routing logic to decide which node is the most suitable in every moment to send the sensor information to, so it gets to the DPC.
- The MNOE communicates with the WiMAX transceiver. In order to do this, it is aware of the commands the WiMAX node understands, and uses protocol xml-rpc to communicate these commands.
- The MNOE has also the ability to store information from the WiMAX transceiver. For example, if a mesh node is at a distance of three hops from the DPC, the mesh nodes in the path of the source mesh node and the DPC will be storing this information in between reliable hops. In order to do this, the communication between two mesh nodes will go from MNOE to MNOE.

According to this description, we can think about a generic mesh node as it is shown in the next figure:

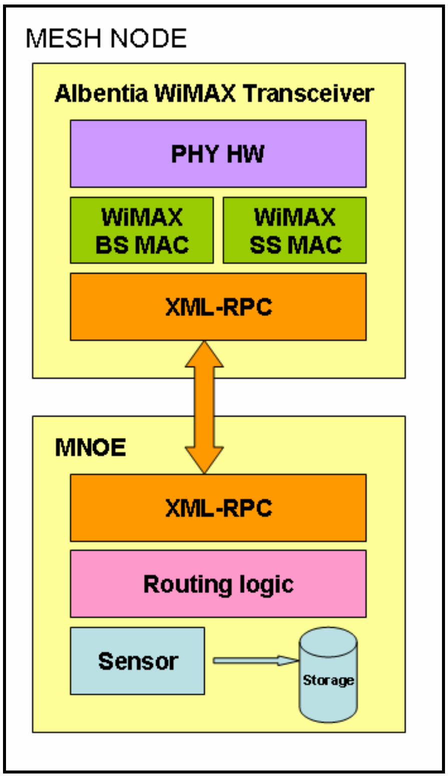

Figure 5-1: Mesh Node.

In this case we have assumed that the weather sensor is integrated inside the MNOE, but this is not mandatory. Nevertheless, the MNOE needs some storage capacity to save information until its transmission is possible.

5.2 XML-RPC: INTRODUCTION AND USAGE.

XML-RPC is a remote procedure call protocol which uses XML to encode its calls and HTTP as a transport mechanism.

It is a very simple protocol because it only defines a few common data types, some useful commands and a complete description of short extension. The simplicity of XML-RPC is in contrast with many other RPC protocols which have a long and wide documentation and they require considerable SW support.

Inside the http-request (POST method), we will find the xml code with the remote procedure call. A very simple procedure call/response example is shown in the next piece of code:

```
POST /xml-rpc/monitorization.cgi HTTP/1.1
Content-Type: text/xml
User-Agent: MNOE
Authorization: Basic eG1sOnhtbA==
Host: 192.168.50.174
Content-Length: 196
Connection: Keep-Alive

<?xml version="1.0"?>
<methodCall>
  <methodName>SetOperationMode</methodName>
  <params>
    <param>
      <value>
        <i4>1</i4>
    </value>
   </param>
  </params>
</methodCall>
```

```
HTTP/1.0 200 OK
Status: 200 OK
Content-type: text/xml; charset="utf-8"
Content-length: 156

<?xml version="1.0" encoding="UTF-8"?>
<methodResponse>
  <params>
    <param>
      <value>
        <i4>0</i4>
    </value>
   </param>
  </params>
</methodResponse>
```

In this case the method call of the command "SetOperationMode" needs a parameter of type "i4" – four byte signed integer – that in this particular case has value 1.

The method response in this case returns 0 (success), but it may return any other parameter or a "fault" tag, indicating an error on the procedure execution.

To send/receive xml-rpc commands it necessary to have client/server http architecture established between the two sides of the communication.

5.3 INTEGRATION OF XML-RPC IN THE WIMAX MESH NODE.

The architecture adopted in the WiMAX node needed to be as simple as possible since we are dealing with an embedded device with limited resources.

For its regular configuration, the Albentia Systems WiMAX node has already integrated an http server that executes CGI programs. These CGI programs run in the user land of the embedded system inside the WiMAX transceiver, and they are in charge of calling the necessary C libraries that operate against the WiMAX driver, running in the kernel of the embedded system. The next figure shows this architecture.

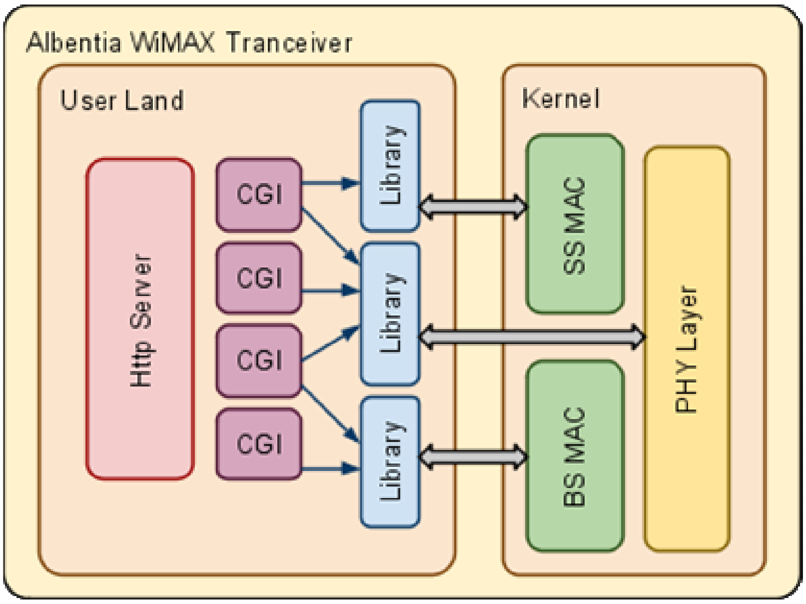

Figure 5-2: Albentia WiMAX Transceiver.

A very simple example would be changing the radio frequency of the WiMAX transceiver. The user will need to have access to the WiMAX node (LAN connection is available), open a Web Browser and call the CGI in charge of presenting the radio configuration. After this, the user will change the parameter in the form ad-hoc, and send the http-request containing: the name of the CGI in charge of making these changes, and the form with the parameters to change and the new values to set on them.

The http-server will take the request, call the proper CGI and, after reading the form with the in-parameters and making the necessary verifications, the CGI will call the proper library method in charge of the radio frequency changes, with the new frequency value. This library makes a call to the driver that changes the radio frequency as selected. The result of the operation goes up to the CGI and the CGI will build the proper response. The http-request is sent back to the user Web Browser.

In this example, commands get to the WiMAX node inside the http-request that addresses the CGI in charge of the operation, and contains the form with the new radio parameters. The CGI is capable of understanding this form and, eventually, the proper function inside the driver is called.

Instead of a web form, to make procedure calls from the MNOE, this one will have to insert xml-rpc code inside the http-request and send them to the WiMAX node. Once there, the http-server will call the CGI referred in the request, and the CGI will need to use a new element capable of understanding the xml-rpc command and "translate" this information for him. This new element will be the xml-rpc library called "xmlrpc_c". After that, the CGI will be able to proceed with the calls to the driver.

To sum up, the main tasks needed to be performed in the WiMAX node are:

- Creation of the CGI in charge of dispatching the requests from the MNOE.
- Integration in the WiMAX embedded platform of the library xmlrpc_c so it can be called from the new CGI.
- Design of the xml-rpc commands needed for the mesh operations: protocol specification.

- Implementation inside the WiMAX node of all the functions required to perform the mesh commands. These commands will affect the driver and the user space of the embedded system.

The previous diagram with the new items included is presented in the next figure. In this case, we only make reference to the new MNOE.cgi, in charge of dispatching the http-requests with the xml-rpc commands included.

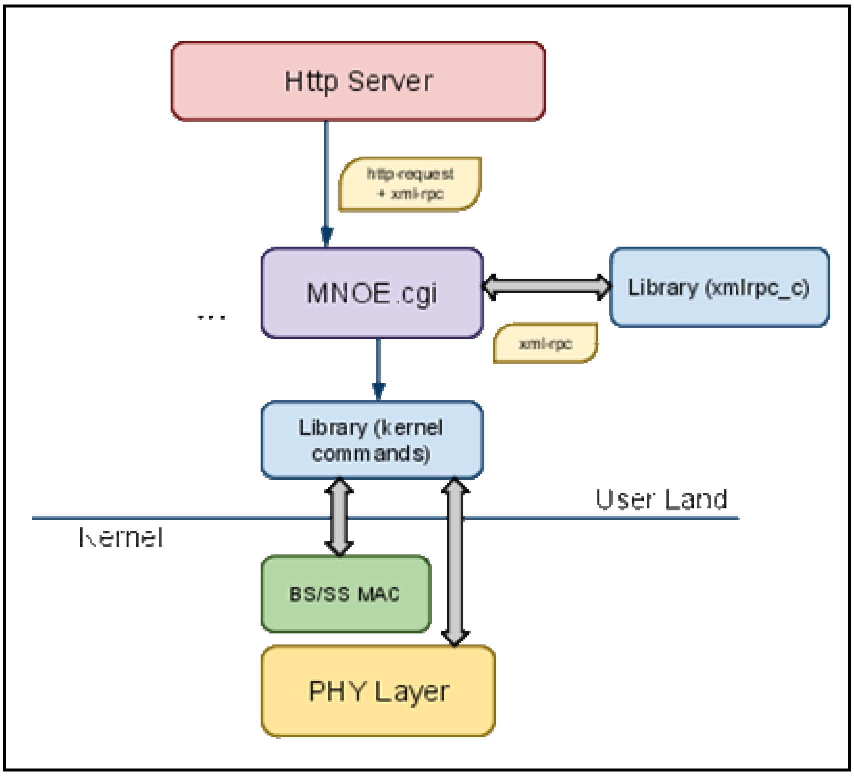

Figure 5-3: Albentia WiMAX Transceiver with (xml-rpc integrated)

5.4 PROTOCOL SPECIFICATION.

As in any kind of communication involving client server architecture, both sides must agree in the protocol they will be using. Xml-rpc will be the language adopted, but the commands, parameters, and error formats must be shared by both the MNOE and the Albentia WiMAX equipment.

Therefore, it is mandatory to define a protocol specification that will establish the necessary frame for a correct and coherent exchange of information between the two agents involved. This protocol specification will serve as guideline to both agents to implement the request/response code and the functionality these operations brings.

Every call defined in the protocol needs to specify:

- Name of the command.
- Semantics: brief explanation of the purpose of the call.
- Calling parameters.
- Returning data.

5.4.1 Protocol available calls

In the next table there are listed the necessary calls that MNOE and the WiMAX transceiver exchange for the mesh operation:

Command Name	Semantic
StopMAC	Stops the operation of the driver at the MAC layer. Link will be interrupted.
StartMAC	Starts the operation of the driver at the MAC layer. If the equipment is configured correctly, link will be established.
GetOperationMode	Returns the mode the WiMAX transceiver is operating as (BS/SS).
SetOperationMode	Sets the operation mode of the WiMAX transceiver (BS/SS)
GetNetworkConfiguration	Returns the network configuration that the WiMAX transceiver is using.
SetNetworkConfiguration	Sets the desired network configuration to the WiMAX transceiver.
GetRFConfiguration	Returns the RF configuration of the WiMAX transceiver.
SetRFConfiguration	Sets the RF configuration of the WiMAX transceiver.
LoadProvisionFile	Starts transfer of a provision file. In case every configuration brings a different set of service flows creation, this command will be needed when switching to BS operation mode.
IsTransmissionAllowed	This command will force the WiMAX node to assure that the (TX) service flows that where supposed to be created in previous calls, are actually processing traffic.

Table 5-1: Protocol specification - Commands.

6. EXAMPLE SCENARIO

In this chapter we are going to describe an example scenario developed for the project. This scenario has four mesh nodes, plus the DPC that will act as a fifth node.

In order to operate as a mesh network, it is necessary to plan a periodic operation of the mesh nodes that involves certain synchronism between them[1]. We will refer to the main period of operation of the mesh network as T_{MN} . This period is divided into three different lapses of time, and the network configuration will change in every one of this lapses. We will refer to these lapses as states of the network, and the time the network remains in each state will be referred as T_{Si} (time spent in state "i").

Also, it is necessary to keep in mind that transitions between states take their time too, so we need to add to the n-states T_{Si} , as many T_{SW} (time spent in switching from one state to the next one) as operating states the mesh network has. In our case, the total period of the mesh network is:

$$T_{MN} = T_{S1} + T_{S2} + T_{S3} + (3 \cdot T_{SW})$$

In the next sections we will see how traffic flows in every period of configuration in a different way, depending on the links established in that period. It is in the scope of this document to describe the main configuration parameters needed to switch from one state to the next one, and understand how in every state switch, the MNOE communicates these parameters to the WiMAX transceiver.

We will see the level of redundancy we obtain with this topology, and we will make several calculations over the latency the network may have and how it is important to set properly the duration of state periods in order to maintain the latency as low as possible.

Regarding throughput, we will make some estimation with the help of an example about the throughput available when sending information between a particular node and the DPC.

Finally, we will see how it will be necessary for the nodes to have certain DTN characteristics since there will be always a delay between the arrival of data to a mesh node, and the transmission of this data to the next mesh node (at least one state period of wait). We will make an estimation of the storage capacity needed.

6.1 MESH NETWORK STATES

Following, the three states of the mesh network will be depicted. In every state, it is possible to identify what has been called as "Areas". Every area has its own RF configuration, and service flows are created to allow data transmission between the nodes that communicate inside the area. In these examples, we have shown the necessary flow services to transmit data to the DPC, but service flows from the DPC to the nodes will be also necessary to allow interrogation of the DPC to the network mesh nodes.

It is important to notice that the sum of all the areas of the three states gives a total coverage of the mesh network, allowing the communication between the DPC and the mesh nodes through multiple paths.

[1] It will be necessary a signalling protocol between the MNOEs so, in case synchronism is lost, it can be recovered. The implementation details of this recovering mechanism are out of the scope of this document.

6.1.1 State 1

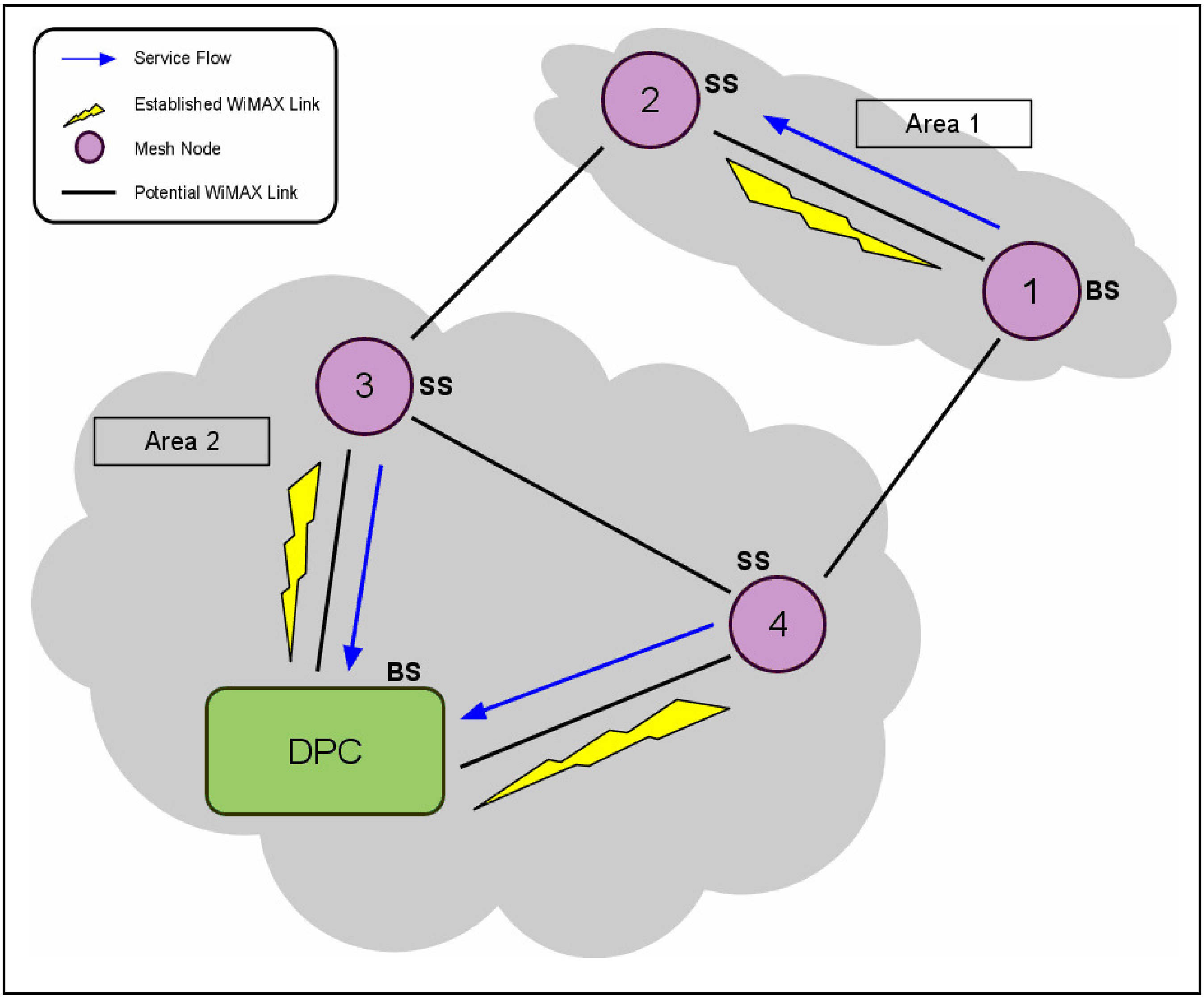

Figure 6-1: State 1.

Nodes sending data: 1 (DL service flow), 4 (UL service flow) and 3 (UL service flow).
Nodes receiving data: 2 and DPC.
Working time for this scenario: from T_0 to T_{S1}

6.1.2 State 2

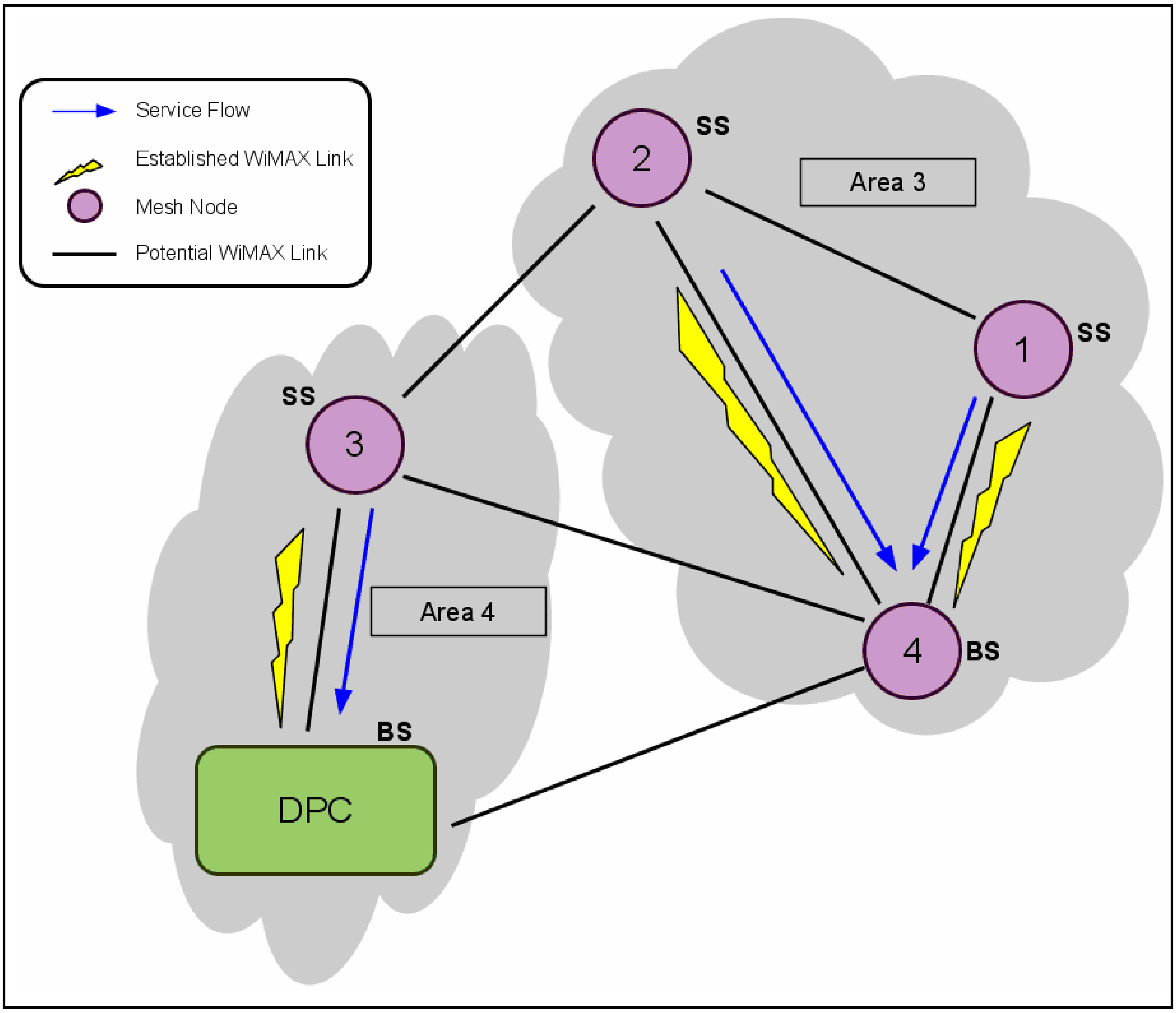

Figure 6-2: State 2.

Nodes sending data: 1 (UL service flow), 2 (UL service flow) and 3 (UL service flow).
Nodes receiving data: 4 and DPC.
Working time for this scenario: from ($T_{S1} + T_{SW}$) to T_{S2}.

6.1.3 State 3

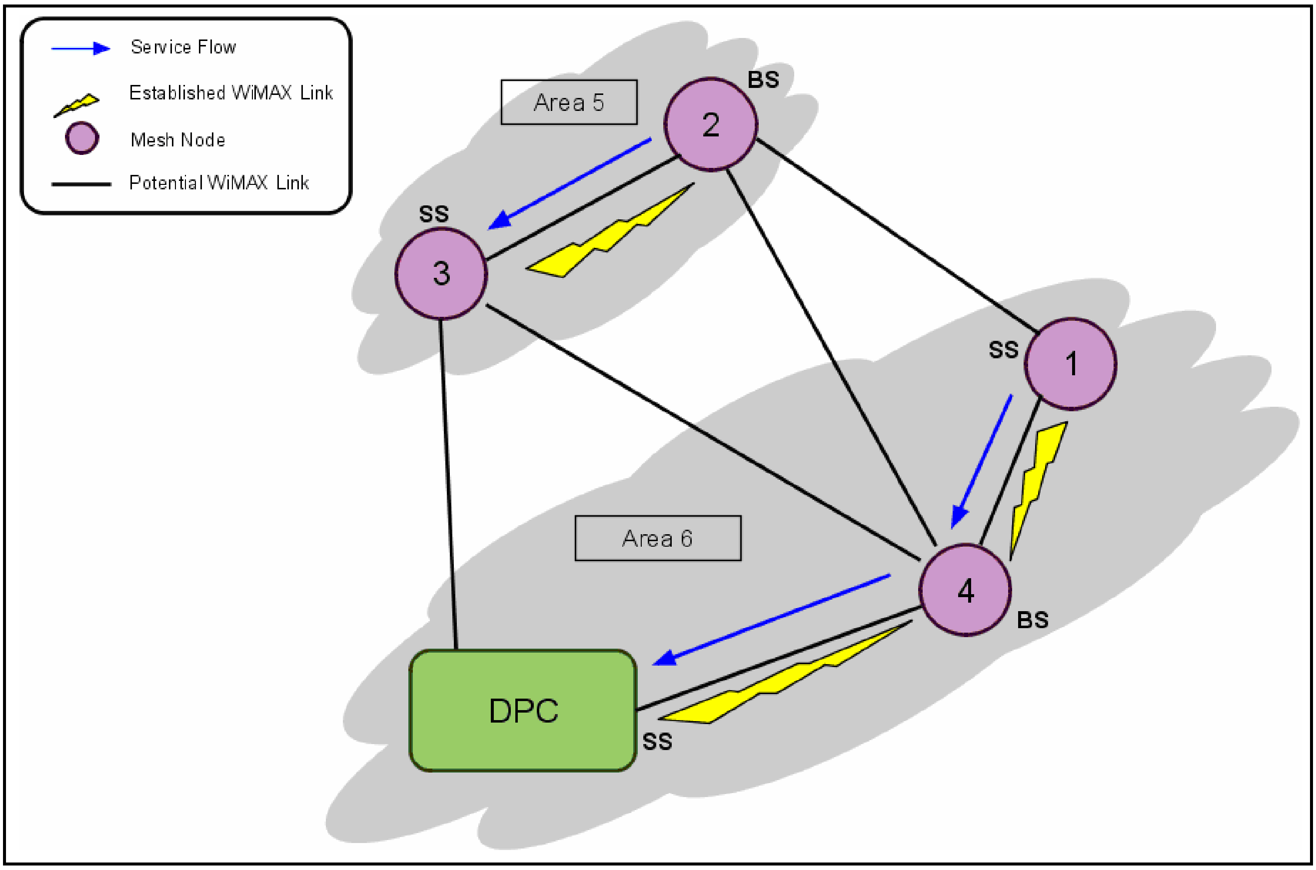

Figure 6-3: State 3.

Nodes sending data: 1 (UL service flow), 4 (DL service flow) and 2 (DL service flow).
Nodes receiving data: 4, 3 and DPC.
Working time for this scenario: from (T_{S2} + T_{SW}) to T_{S3}.

6.2 SWITCHING BETWEEN STATES

To study the switching process, we can study the changes necessary between state 1 and state 2 on the mesh node number 4. In this transition, node 4 will change its operation mode from SS to BS.

The following diagram explains the xml-rpc commands that the MNOE of node 4 will be exchanging with its WiMAX transceiver.

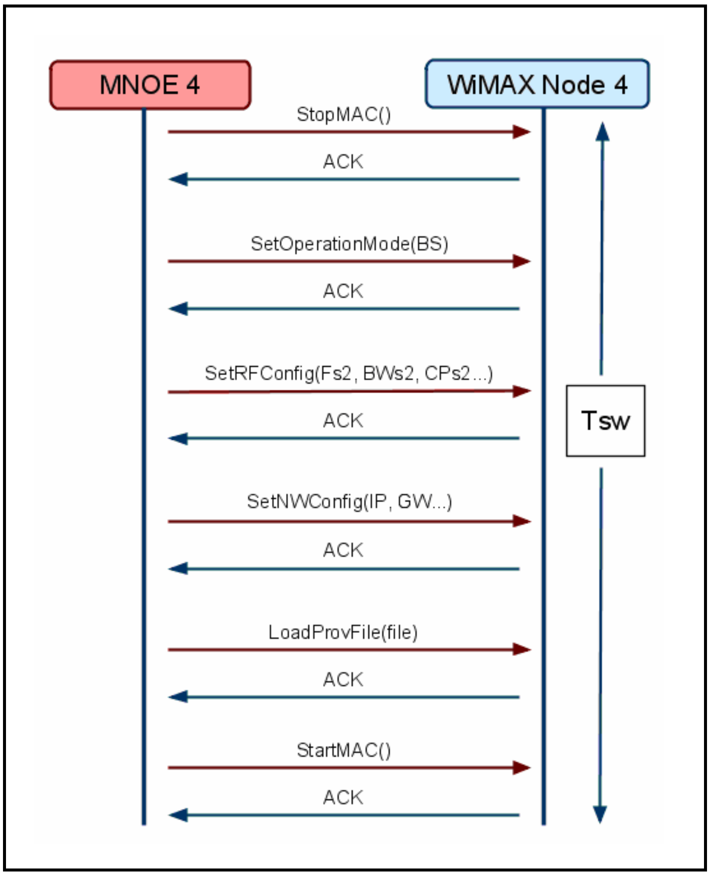

Figure 6-4: Time Diagram for switch 1 to 2.

There is another important call that will be made after the "StartMAC" command in nodes that change configuration to a sending data configuration, for example node 1. This call is "IsTransmissionAllowed" and if returns true, any data pending of transmission in node 1 will be sent to node 4.

6.3 NETWORK CHARACTERISTICS: REDUNDANCY, LATENCY THROUGPUT, DELAY TOLERANCE.

6.3.1 Redundancy

If we observe the three states again, we see that there are certain nodes that have redundancy in their paths to the DPC. Depending on the state period in which the data transmission is solicited, data will flow through any of the paths available. The following table shows the "next hop" available depending on when data is ready, and on the source node of the information.

	Data Ready in State 1	Data Ready in State 2	Data Ready in State 3
Node 1	Node 2	Node 4	Node 4
Node 2	Cannot transmit	Node 4	Node 3
Node 3	DPC	DPC	Cannot transmit
Node 4	DPC	Cannot transmit	DPC

Table 6-1: Next Hop depending on data source and time.

The table shows that:

- Node 1 can transmit at any time. The most probable path is 1 – 4 – DPC and in the case Node 4 is not operative, information will still get to DPC through the path 1 – 2 – 3 – DPC. Redundancy is assured for this node.
- Node 2 can transmit in states 2 and 3. In the first case the path will be 2 – 4 – DPC and in the second case 3 – DPC . Here again redundancy is assured.
- Node 3 is allowed to transmit in states 1 and 2, but there is no redundancy on paths.
- Node 4 is as well allowed to transmit in states 2 and 3, but there is no redundancy of paths.

We can think of other states that might give more redundancy to nodes 3 and 4, but these issues are out of the scope of this document that only pretends to give an example scenario.

6.3.2 Latency

Based on table 6.1 we can derive another one that will show latencies. We will make this estimation assuming that all nodes are fully operative and the chosen path only depends on the data source and the moment data transmission is solicited.

	Data Ready in State 1	Data Ready in State 2	Data Ready in State 3
Node 1	T_{MN}	$2 \cdot T_{SW} + T_{S2} + T_{S3}$	$2 \cdot T_{SW} + T_{S3} + T_{S1}$
Node 2	T_{MN}	$2 \cdot T_{SW} + T_{S2} + T_{S3}$	$2 \cdot T_{SW} + T_{S3} + T_{S1}$
Node 3	$T_{SW} + T_{S2}$	$T_{SW} + T_{S2}$	$2 \cdot T_{SW} + T_{S3} + T_{S1}$
Node 4	$T_{SW} + T_{S2}$	$2 \cdot T_{SW} + T_{S2} + T_{S3}$	$T_{SW} + T_{S2}$

Table 6-2: Latencies depending on data source and time.

For example, if node 1 has available data to be sent during the state 1 the following process will take place:

- Data transmission between node 1 and node 2 during state 1. Consumed time → T_{S1}
- Switch states from 1 to 2. Consumed time → T_{SW}
- Data transmission between node 2 and node 4 during state 2. Consumed time → T_{S2}
- Switch states from 2 to 3. Consumed time → T_{SW}
- Data transmission between node 4 and CPE. Consumed time → T_{S3}

If we add the switching time necessary before state 1 is stable, we have the complete T_{MN} as shown in the table.

From this information we can delimit latencies going from $T_{SW} + T_{S2}$ (best case), to a complete T_{MN} (worst case).

6.3.3 Throughput

The throughput of the network depends on various factors. For this calculation we will make the following assumptions:

- All service flows are provisioned with the same rate, and same QoS. For this example let's think about UGS service flows with 15Mbps.
- Radio conditions are the best possible, so UL/DL modulations are always 64 QAM ¾.
- We need to focus on the complete path, this is, if we keep considering that information goes from nodes to the DPC, we want to know the maximum throughput between "node i" and the DPC.

We can assure 15Mbps between nodes in the T_{Si} periods where the "node i" can transmit, which are not all the periods; and besides this, we also need to take into account the T_{SW} time, that affect to all nodes where all throughput is interrupted.

The following table present the throughput considering **T_{SW} = 30s and T_{Si} = 100s**

	Throughput
Node 1 – DPC	15 Mbps · $(T_{S1} + T_{S2} + T_{S3}) / T_{MN}$ = 11,5 Mbps
Node 2 – DPC	15 Mbps · $(T_{S2} + T_{S3}) / T_{MN}$ = 7,7 Mbps
Node 3 – DPC	15 Mbps · $(T_{S1} + T_{S2}) / T_{MN}$ = 7,7 Mbps
Node 4 – DPC	15 Mbps · $(T_{S1} + T_{S3}) / T_{MN}$ = 7,7 Mbps

Table 6-3: Throughput

6.3.4 Delay tolerance

As we mentioned through the entire document, it is important that this mesh network has characteristics of a DTN. This means that our MNOE's might need to perform as DTN routers, being the main characteristic of such devices, the storage capacity they need in order to assure information doesn't get lost during the lapses of time the network is not processing traffic.

We can make an easy calc to delimit the minimum storage capacity needed considering the same numbers of the last section. The DTN device needs to be able to storage at least all the information received during a connection time T_{Si} . This capacity should be increased though, if we consider that, given a certain mesh node, at the same time information arrives from its neighbours, the proper information coming from its sensor might be also ready to send. If we add this variable, we would need to know the sampling period of the weather sensors, and the size of each sample. Nevertheless, we will consider for this calc that this sampling rate is much bigger that T_{MN} and that the size of each sample is not significant when comparing to the information that may arrive during a connection time.

With all these premises taken into consideration, the minimum storage capacity for each mesh node is the same, since all flows are equally provisioned:

Storage Capacity = 15 Mbps · 100 s = 1500 Mbits