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Analysis of Reconfigurability, Control and Resource Management in Heterogeneous Wireless Networks

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Abstract: Modern communications networks integrate different access technologies that require interoperability for seamless and user-transparent transfer of multimedia-reach content. Latest standardization activities in this area pinpoint the IEEE 802.21 standard as an enabler of media independent handovers in various scenarios. Additionally, the implementation of the heterogeneous network paradigm yields optimized and efficient resource management techniques emphasizing the need for reconfiguration and interoperability capabilities within future wireless networks. This paper analyzes a combination of reconfigurability, interoperability and resource management aspects in heterogeneous wireless networks based on the IEEE 802.21 standard. It introduces a novel platform for wireless heterogeneous communication systems and a prototype of a reconfigurable mobile terminal that rely on the IEEE 802.21 standard. The introduced platforms are extensively validated through simulations and laboratory experiments showcasing that the IEEE 802.21-backed interoperability is able to support uninterrupted content delivery across multiple communication technologies with high performance.
Keywords: Heterogeneous Networks; Resource Management; IEEE 802.21; Simulation; Prototyping.

1 Introduction

The exponential growth of the wireless mobile traffic, both voice and data, poses new requirements on the future networks [1]. Recent study from ABI Research [2] shows that the global volume of mobile data traffic will exceed 107 Exabytes in 2017. Furthermore, the proliferation of internet-connected mobile devices will continue to grow, forcing networks operators to dynamically increase the capacity of their networks.

Contemporary end-user mobile devices integrate a plethora of radio access technologies including 3GPP/3GPP2-based technologies as well as non-3GPP-based technologies such as Wi-Fi and Bluetooth. This terminal side heterogeneity drives R&D efforts towards efficient interworking and seamless transition among different air interfaces. The transparent transition between multiple Radio Access Technologies (RATs) is usually referred to as vertical handover (VHO). The existence of multiple different RATs triggered a development of Self Organizing Networks (SONs) that address heterogeneity in the wireless networks by introducing efficient and self-controlled methods for seamless VHOs. In addition, the heterogeneous wireless networks have a broader meaning than just a network whose radio access part comprises several air interfaces belonging to a same wireless system family (e.g. 2G, 3G and beyond). This concept needs to consider other, i.e. non-3GPP-based, wireless networks such as Wi-Fi and WiMAX, forcing new and specific solutions for transparent interworking. The introduction of the heterogeneous networking leads to resource management approach shift from technology-centric to consumer-centric. The heterogeneity is reflected in two main concepts, i.e. multiple different networks and multiple different layers in one RAT (i.e. network cell densification). Its presence in future wireless networks yields ubiquitous services through multiple communication interfaces in a user-transparent manner.

Several international standardization bodies have taken steps towards including radio access heterogeneity in contemporary wireless systems. The enclosure of VHOs between different RATs in several existing standards paved the way for major advances and network efficiency improvement, as one of the main tools for efficient Radio Resource Management (RRM) in modern heterogeneous networks. 3GPP Release 8 (LTE) made one of the most significant contributions towards adopting and standardizing the heterogeneous networks and exploiting the benefits from their deployment [3], [4]. The previous, third generation release, provided the necessary technical specifications for wireless system interworking and introduced the VHO as an important RRM functionality that may provide uninterrupted, seamless and ubiquitous wireless connectivity and traffic offloading with more efficient radio resource utilization [3]- [5]. However, in this release, the specifications mainly focus on seamless and transparent handover between different Radio Access Networks (RANs) and air interfaces of the legacy 3GPP cellular systems such as GSM and UMTS. In Release 8, besides additional enhancements and new interfaces for interworking and VHO between the Evolved UTRAN (E-UTRAN) and legacy 3GPP RANs, 3GPP extends and utilizes the concept of VHO even further. In particular, interworking with non-3GPP RANs is one of the key design goals for the novel and evolved system architecture (SAE). The non-3GPP Interworking System Architecture in LTE includes a set of solutions in two categories. The first category contains a set of generic and loose interworking solutions that can be used with any other non-3GPP RAN (such as IEEE-based wireless systems). Mobility solutions defined in this category are referred as Handovers without Optimizations. The second category includes a specific and tighter interworking solution with one selected RAN, i.e. the cdma2000 High Rate Packet Data Air Interface. This solution category is called Handovers with Optimizations. As specified, the non-3GPP Inter-working System Architecture in LTE completely leverages on flat architecture of E-UTRAN and the flexibility and modularity of SAE. HP has proposed another state-of-the-art implementable solution that belongs to the first heterogeneity concept with multiple RATs [6]. The basic idea is to enable the communication service providers to streamline the transition to long-term evolution (LTE) and embrace a diversity of mobile access networks with a single subscriber management solution. The new HP solution bridges 2G, 3G, 4G, Wi-Fi and IP Multimedia Subsystem (IMS) networks to enable service providers to centrally manage subscribers' profiles, regardless of the networks to which they are connected.

Another example is the solution proposed by Nokia-Siemens, named Smart Wi-Fi [7]. It is a carrier-grade, end-to-end solution for building, optimizing and controlling Wi-Fi networks that integrate seamlessly with cellular networks. The need for general system interworking framework led to the initiation (in 2004) of the IEEE 802.21 standard, which was published in 2008 [8]. The standard supports various technical solutions that enable seamless VHOs introducing the so called Media Independent Handover (MIH). In particular the standard allows transparent interoperability among different underlying technologies such as 802.3, 802.11, 802.15, 802.16, 3GPP and 3GPP2 families. The forthcoming subsections present and elaborate on IEEE 802.21 standard as an important general system interworking framework for heterogeneous networks.

All previous examples belong to heterogeneity cases with multiple RATs. According to the other concept, multi-layering in a single radio access technology can also provide heterogeneity in the network. The growing demand for affordable mobile broadband connectivity is driving the interest towards implementation of a multitude of small cells, such as micro, pico and femto cells. Small cells were used mainly for fill-in purposes to improve the network coverage in the early days of GSM and until recently with HSPA. Today, there is a constant outdoor small cell (micro and pico) densification, which is cost-effective and relatively simple option for adding capacity to the wireless network. For indoor traffic offload, femtocell deployment (with the so-called Home eNodeB) represents a promising solution [9], [10], where the end users are making the deployment without any interaction of the network operators. Since more than 80 per cent of global wireless data traffic will be generated indoor [11], the femtocell concept will play important role in the future cellular networks. Recently, several international standardization committees have expressed their intents to provide standardized approach towards wireless network densification. 3GPP Release 10 and LTE-Advanced (LTE-A) [12] introduce a number of technical specifications towards small cell deployments and network densification with strong emphasis on femtocell deployments. The LTE-A evolved framework for Inter-Cell Interference Coordination (eICIC) and the support for Self-Organization, provides two types of multilayer coupling. The first type comprises closely coupled cells (such as macro cells), which are subjected to frequency planning and RRM. The second type consists of loosely coupled cells (e.g. picocells or femtocells) that auto-configure and auto-optimize and provide frequency reuse with factor one. Both types of cell coupling exploit the X2 interface for coordination. It is expected that the network densification process and the aggressive frequency reuse will enable dramatic increase in wireless capacity, data rates and quality of user experience [13].

Among many previously mentioned examples and approaches to cope with the problems related to the heterogeneous networks, this paper focuses on the IEEE 802.21 standard as the enabler of VHO in heterogeneous networks. It provides extensive simulation-based validation of the IEEE 802.21 heterogeneous network performance in various scenarios. The potentials of the standard for seamless interoperability are extensively exploited to develop a complete solution for reconfigurable and interoperable network resource management (RM) mechanisms for heterogeneous environments. The proposed platform is then tested and validated in a state-of-the-art laboratory simulator and is completely ported to a laboratory prototype of a reconfigurable multi-interface mobile terminal. Up to the best of authors' knowledge, this prototype is the first in the literature that relies on the IEEE 802.21 standard and incorporates an advanced RM.

2 Reconfigurability and Interoperability in Heterogeneous Networks

The modern network devices now include a plethora of built-in communication interfaces, of both wired and wireless type. The most popular consumer electronic devices such as tablets, laptops, personal digital assistants or even smart-phones are supporting wideband connectivity through both cellular technologies and Wireless Local Area Networks (WLANs). At the same time, communication devices are capable of exchanging, processing and displaying multimedia-reach contents in real time [1]. These new multi-access devices push the boundaries of the modern communications towards a network environment that is referred to as the fourth-generation of mobile communications (4G). The major benefits of the previous third-generation (3G) communications involve increased data rates (compared to the second generation of mobile devices), seamless mobility within large geographical areas, along with a global reachability. The biggest challenge for the 4G networks includes beyond transparent mobile communication within only one access network, and a global reachability in form of anytime, anyplace using heterogeneous communication technologies. For this purpose, different communication technologies need to integrate into a single heterogeneous platform [15]. This platform should be capable of supporting user transparent roaming and efficient delivery of multimedia traffic. On the other hand, the terminal devices participating in a heterogeneous network need to be able for autonomous operation, requiring the capability of self-reconfiguration. As a result, the notion of VHO in heterogeneous scenarios becomes a necessity. The VHO concept requires the need to research and develop novel solutions that support interoperability among different communications technologies. This gives rise to the concept of reconfigurable interoperability [16].

The reconfigurable interoperability is a cornerstone of modern communications and is essential driving force towards the multimedia content delivery in heterogeneous environment. The reconfigurable interoperability can be obtained on network side, on user side, or on both. This brings benefits for both, network providers and users. At the same time it contributes to the robustness of the provided services, allowing seamless and transparent network management.

When implemented on network level, the reconfigurable interoperability enables the network providers with a possibility to choose between a variety of wireless access networks. In this case, the access technology selection could be based on several criteria, such as:

- Comparison of access resources availability and specific service requirements (e.g. channel state, outage probability, VHO probability, user QoS requirements, context awareness etc.);
- Traffic load sharing and distribution between different coexisting networks;
- Efficient spectrum sharing;
- Network discovery and preferred gateway selection;
- Network congestion;

When implemented on user side, the reconfigurable interoperability will lead to more efficient end-to-end connectivity and service delivery in heterogeneous environments, easier worldwide roaming and dynamic adaptation to regional contexts, enhanced personalization and richer services. The users' terminal devices can reconfigure based on:

- Available resource capabilities;
- Minimization of the service cost when multiple underlying technologies are available;
- Anticipation of communication quality, as well as user contexts and preferences;
- User's mobility [17].

Autonomic decision making and self-healing capabilities directly provided by the reconfigurable interoperability can greatly improve the communication reliability. Furthermore, network providers can use the reconfigurability to introduce the value-added services more easily. They can exploit these features at the application level, since they have the possibility to introduce new services of various types. This will lead to more vibrant market movement and increased consumers' choices.

The reconfigurable interoperability in future convergent and multimedia reach communications must not be provided by isolated proprietary and vendor related solutions (such as Nokia's multimode Unlicensed Mobile Access - UMA concept), but rather should be supported by internationally recognized standard, like IP Multimedia Subsystem (IMS) and LTE's Evolved Packed Core (EPC) - based solutions. These approaches address the aspect of interoperability and VHOs by incorporating variety of advanced mechanisms (e.g. PCC [15], SRVCC [19], [20] PMIP [21], etc.) that support the VHO processes. As discussed in [22], the known solutions show handover performance inconsistencies that lead to degradation and in worst case complete failure of the handover procedures. This is where the new IEEE 802.21 standard positions.

The following two subsections will give an overview of the IEEE 802.21 standard, along with the necessary validation of its benefits in reconfiguration and inter-operation of heterogeneous networks.

2.1 IEEE 802.21 standard and Network Reconfiguration

The IEEE 802.21 standard [16] is a result of the work performed within the Media Independent Handover Services group of IEEE. The working group has been initiated in 2004 and the latest draft version of the standard was accepted in November 2008. The standard itself has been published in January 2009. The actual deployment of the standard is taking place at the moment and is predicted to intensify in the near future.

In the heart of the IEEE 802.21 framework lays the Media Independent Handover Function - MIHF. All IEEE 802.21 compatible devices should contain a MIHF in order to provide communication with different terminals, networks and remote MIHFs. MIHF provides abstract services to the higher layers (MIH User) using a unified interface (located on layer 2.5 according to the Open System Interconnection-OSI reference layer model). MIHF defines three different services: *Media Independent Event Service (MIES)*, *Media Independent Command Service (MICS)* and *Media Independent Information Service (MIIS)*.

Changes and condition of the Link Layer trigger appropriate MIES events. MICS provides the upper layers necessary commands to manage the link behavior. MIIS provides information about the neighboring networks and their current status and capabilities.

The IEEE 802.21 standard aims to provide transparent communication in heterogeneous environments by enabling seamless HOs between available access technologies. The standard defines mechanisms for network-in-range discovery and execution of intelligent VHOs, based on established link conditions and mobile devises' capabilities and preferences. For instance, WLAN can be preferred when available, instead of expensive cellular network communication, especially for heavy data transfer. As another example, the device can choose the strongest signal network in order to obtain itself with best QoS, or the network can balance traffic load in order to obtain stable communications. Present devices do not possess capabilities for intelligent self-reconfiguration. Users can only manually select the communication technology interface based on their knowledge and review of the network state. IEEE 802.21-capable devices are always aware of the available access networks and changes in link conditions. By combining this information with some intelligent RM implemented within mobile devices or on the network side, the communication is getting closer to the envisioned concept of 4G.

The main contribution of the IEEE 802.21 relies on a technology-independent abstraction layer which provides a generic interface to the processes operating on upper protocol layers. In this way the upper layers do not need to be specialized in processing the technology specific primitives, resulting in much simpler and complexity-free upper layer processes. The mobile device maintains a relevant set of networks and link status in a generic manner and the resource manager utilizes this set of information, containing static and dynamic aspects of the links, in order to fulfill its comprehensive decision-making activities. The resource manager can further involve Mobile IP aspects and functions, especially in the handover decision making process.

2.2 Simulation and Validation of IEEE 802.21 based Interoperability

This subsection validates the benefits of the IEEE 802.21 standard by presenting a simulation platform, which combines a commercially available network simulator (QualNet) and a Specification and Description Language (SDL)-based protocol developer [16]. This combination facilitates novel protocols and architectures development and their subsequent validation in a state-of-the-art simulator. The targeted simulation scenario for IEEE 802.21 performance analysis Fig.1 comprises a heterogeneous wireless network (HWN) consisting of two IEEE 802.11 Access Points (APs) providing local coverage, two IEEE 802.16 Base Stations (BSs) providing metropolitan coverage and a satellite network for global scenario coverage. All radio access technologies overlap in order to enable increased connectivity options. There are a varying number of mobile nodes in the scenario communicating with the Correspondent Nodes (CNs) located within the network infrastructure. The users are allowed to move according to the random waypoint mobility model and they exhibit frequent vertical handovers in the scenario, i.e. changing of the Point of Attachment (PoA) which serves the users. All mobile nodes have active constant bit rate (CBR) applications of 64 kbps (voice application) or 2 Mbps (video application). The main performance parameter of interest that is crucial for the entire reconfigurable interoperability paradigm is the Vertical Handover Latency (VHL). The minimization of the VHL value allows seamless vertical handovers in heterogeneous wireless networks and facilitates the RM problem substantially. Its calculation must take into consideration the end-to-end delay of the new serving network and the receiver packet latency once a vertical handover occurs. The former parameter is calculated as:

$$\tau_{e2e}^{i} = t_{rcv}^{i} - t_{sent}^{i} \quad (1)$$

where t_{rcv}^{i} is the packet receive time and t_{sent}^{i} is the packet sent time on the new service network (denoted as network i) when a vertical handover happens. Using (1), the VHL value can be easily derived as:

$$\tau_{VHL}^{ij} = \tau_{L}^{ij} - \tau_{e2e}^{i} \quad (2)$$

where τ_{L}^{ij} is the receiver packet latency (defined as the time difference between the last successfully received packet from the old service network j and the first successfully received packet from the new service network i).

Fig.2a and Fig.2b depict the average VHL value for 30 and 90 mobile nodes in the scenario, respectively. It is evident that the introduction of the IEEE 802.21 functionalities provides significantly lower VHL values, a smaller increase of the VHL value with the increase of the number of mobile nodes and almost constant VHL values regardless of the users' mobility pattern.

Fig.2c depicts a comparison of the average VHL for different application bit rates, low mobility and high number of nodes. The introduction of IEEE 802.21 exhibits lower VHL values for all analyzed scenarios proving its superior performance.

The validation results clearly show that the IEEE 802.21 standard can be foreseen as a suitable reference for enabling seamless vertical handovers, providing user transparent interoperability. In some use cases like high speed mobility or large number of users, the VHL exceeds certain delay requirements for real time applications e.g. conversational video. This negative effect is a result of the congested access networks in the case of large number of users or the use of satellite links in the case of high speed mobility which introduces substantial round trip time.

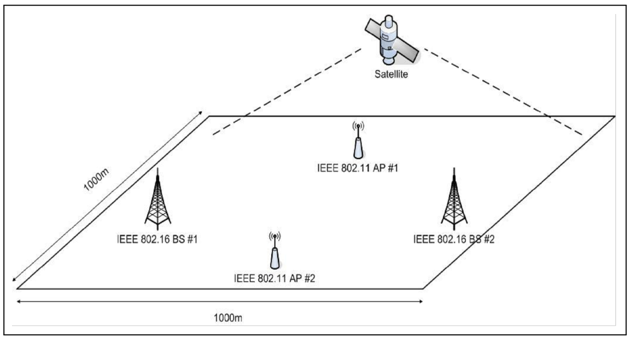

Figure 1: Simulation scenario

In contrast to the simulation scenarios presented here, any real-world system implementations would require a coexistence and interworking of IEEE 802.21 with a number of contemporary

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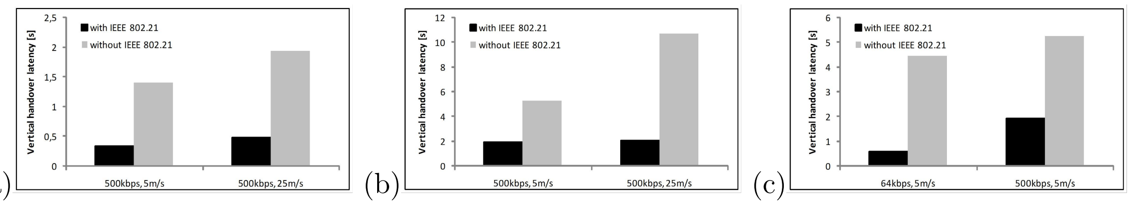

Figure 2: Simulation results: (a) VHL for 30 mobile nodes, (b) VHL for 90 mobile nodes, (c) VHL for different application bit rates

networking solutions like, SIP/SDP signaling, IMS procedures, EPS bearer concepts, etc. In most of the cases the above mentioned coexisting network solutions can be utilized as MIH users and provide the required inter-working capabilities between them and IEEE 802.21. Because the IEEE 802.21 standard envisions a prediction mechanism, all MIH users reconfigure their parameters of interest before the HO occurs, providing a seamless VHO execution that results in a VHL that is impacted only by the IEEE 802.21 HO processes. Hence, the performance of a real-work implementation of the IEEE 802.21 standard is not expected to dramatically defer from the results elaborated in Fig.2.

The following section provides extensive details on how IEEE 802.21 standard is customized and fitted into a novel architecture for providing reconfigurable interoperability of wireless communications systems combining it with an intelligent resource management.

3 IEEE 802.21 Based Radio Resource Management

There are several ideas found in the literature that propose IEEE 802.21 usage for mobility and QoS management support in heterogeneous wireless networks [16]. There are examples of SIP and IEEE 802.21 convergence as a powerful tool for soft vertical handover execution, as well as proposals to use IEEE 802.21 for integration of multimedia broadcast technologies (DVB-H) with other terrestrial access networks. Some works utilize IEEE 802.21 for QoS provisioning in IEEE 802.16 - IEEE 802.11 environment, showing that the assistance of IEEE 802.21 contributes in decreasing the effects of handover latency, jitter and packet loss, thus improving the user perception. Additionally, IEEE 802.21 can be used in a hybrid Satellite - Terrestrial access networks or enable the so called Knowledge Based (KB) mechanism for network selection.
But, a fairly small amount of research work specifically addresses the problem of RM in heterogeneous wireless environment. There are some approaches which are based on Joint Radio RM (JRRM) framework for beyond 3G wireless heterogeneous systems capable of adapting to the resource assignments of the specific system conditions and QoS demands. Unlike related work in the field, the approach presented here enables a fully functional RM mechanism for heterogeneous wireless networks and possesses unique features allowing maximum user servicing and maximum network utilization [16]. In particular, this platform combines RM and reconfigurable interoperability within the principles defined by the IEEE 802.21 standard. As depicted in Fig.3, the MIH User (in this case a RM) resides above the lower MIHF (here denoted as interoperability module - IM). Both components, RM and IM, are located in the end-user equipment. The platform architecture comprises several functional blocks.

Application block: This block presents the user application that requires network resources. Different applications have different needs in terms of bit rate and delay. Furthermore, when making RM decision it is also important what type of user started that application. This message is transferred to the *User and Application Profile* entity (U&AProf). Here the *StartApp* message is processed in *U&A* message that identifies the user class and the application type. The *U&A*

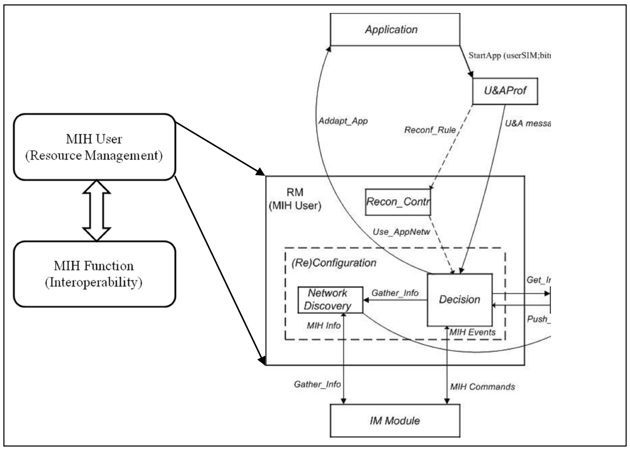

Figure 3: General architecture of the platform

message also presents energy (battery) consumption feature (with two modes of operation: save battery mode and normal battery mode). This information will be used further to select the mode in which the Decision block will operate. The *LRes* repository is a small database that stashes the information regarding the newly detected available networks.

Decision block: This block operates in several modes:

- Emergency Mode,
- BatteryLow Mode and
- Normal Mode.

In the Normal Mode, the Decision block performs simple switching of the user demands to what is available as a resource in the *LRes.* In the *BatteryLowMode*, the Decision block selects the technology that best fits the battery saving constraint, thus reducing QoS (the selected technology may not be best fitted for the application). In the Emergency mode, the RM module uses specially designed algorithm for sorting applications' serving priority.

Network Discovery block: This block has an interface towards the IM module for receiving MIH messages that carry relevant information about the networks in the users' vicinity. It uses *Store_Info* message to fill the *LRes* database and its work is triggered by the Decision block with the *Gather_Info* message.

Recon_Contr block: This block is left for additional reconfigurability constrains. It can learn and store consumers' behavior, thus providing further upgrade of the system (cognition). The ability of this platform to provide reconfigurable interoperability and efficient RM is validated on the same scenario as presented in Fig.1 The results compare the new architecture with the traditional way of serving consumers, i.e. the signal-to-noise ratio (SNR)-based serving policy, where mobile nodes connect to the PoA having the highest SNR value. The performance validation uses a novel performance metric, named *service retainability.* This Key Performance Indicator (KPI) parameter represents the average ratio of the dedicated bit rate to the required bit rate for mobile node, when exhibiting vertical handovers during the simulation scenario. The goal is to maximize the service retainability as its higher values mean that the mobile *node exhibits higher service retention in terms of dedicated bit rate.* Fig.4 presents the simulation results for the dependence of the service retainability on the number of mobile users for the new platform and the SNR based serving policies for 64 kbps and 2 Mbps application data rates. In particular, Fig.4a proves that the new architecture exhibits *increased service retainability* for 64 kbps application data rates regardless of the number of mobile users and the users' mobility. Fig.4b depicts the new architecture behavior in terms of service retainability for 2 Mbps application data rates. It is evident that the proposed platform *outperforms* the SNR based serving policies and that maximum gains are achieved for low number of mobile users.

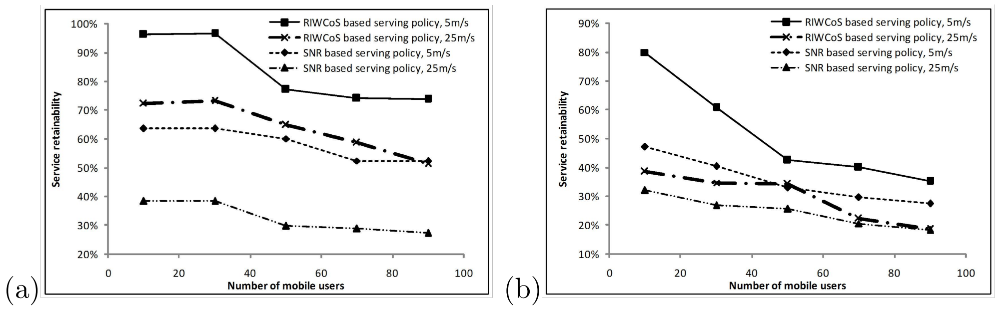

Figure 4: Simulation results: (a) Service retainability for 64 kbps application, (b) Service retainability for 2 Mbps application

Relying on the IEEE 802.21 standard, the proposed architecture is able to cope with RM issues in more efficient manner than the traditional methods proving its soundness for different consumer applications.

The next section will present the prototyping process of a developed consumer terminal which is capable of reconfigurable interoperability based on IEEE 802.21 principles [23]. The section explains different aspects of the reconfigurable terminal design and testing process.

4 Reconfigurable Terminal Prototyping

4.1 Terminal Architecture

In general, the terminal architecture overlays the Network Driver Interface Specification (NDIS) library. It is a standard application programming interface (API) for Network Interface Cards (NICs). A Media Access Controller (MAC) device driver wraps the details of NICs hardware implementation in such a way that all NICs for the same media can be accessed using a common programming interface. In this manner, the terminal architecture includes NDIS client sublayer, radio RM module (RRM) with MIHF and Video Data content used for transmission (Fig.5).

The NDIS library provides the features of NDIS protocol (NDISProt), which connects directly with the NIC hardware. The NDIS client sublayer coordinates the work of all entities, enabling the reconfiguration function through the Main Thread. The ReadHandler and the WriteHandler are the key features controlled by the Main Thread that provide data communication between the content located in the Content Block and the NICs hardware. The test scenario uses video data, where the Main Thread controls the video content in terms of segmentation of packets according to the transmission parameters. The WriteHandler additionally prepares the packets by adding data payload and appropriate Ethernet, IP, UDP and TFTP headers.

Before transmitting of any data, the Main Thread sends information about the network availability to the RRM through the MIHF. The logic of selection an appropriate communication interface depends on the decision made by the RRM module. The RRM and the MIHF are designed and functionally tested by using Specification and Description Language (SDL). The RRM module receives and sends MIH information from and to the NDIS client sublayer in order

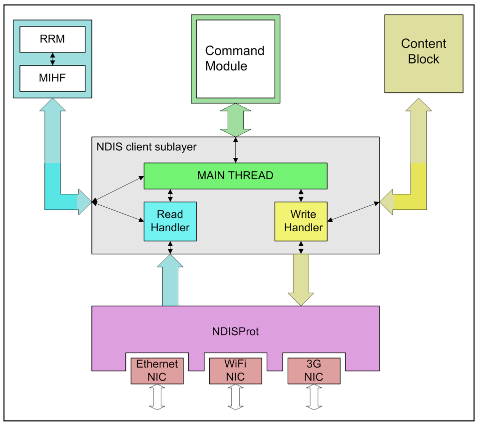

Figure 5: Terminal architecture

to enforce the usage of the most suitable network interface. The decision algorithm is simple and it ranks the three available technologies by priority (Ethernet, WLAN, UMTS). When there is no Ethernet connection available, before using the WLAN, the signal strength of the WLAN is inspected. If this value is lower than a predefined threshold, the WLAN interface is not selected and the packets are send on the UMTS communication interface. The RRM makes decision for using WLAN if the inspected signal strength is above the satisfactory level. The handover between the wireless networks (WLAN/UMTS) occurs when the WLAN signal drops under a predefined threshold set by the RRM.

A Command Module is specifically developed for the Ethernet/WLAN handover in order to overcome a possible blocking of communication during unplugging of the Ethernet cable.

4.2 Testing Scenario and Results

Fig.6 presents the testing scenario setup of the developed reconfigurable terminal. The Correspondent Node (CN) and the reconfigurable Mobile Node (MN) are both attached to the same local network. Consequently, the traffic flow when using Ethernet and WLAN does not rout outside the local network. However, when using UMTS the traffic flow is routed from UMTS towards the CN through Internet (as a global network). The testing scenario begins while the Ethernet cable is connected. When the cable is removed, the terminal is within WLAN coverage and performs vertical handover to the available WiFi access point (AP). As the terminal moves away from the AP, the WLAN signal level drops. When the signal is under a predefined threshold, the MN conducts a vertical handover towards the UMTS network.

The communication performance generally depends on the networks configuration (radio parameters, local or global networks) and hardware configuration (NIC, operating system, etc.) and is denoted by the achieved throughput and inter-packet delay. Fig.7a and Fig.7b depict the measured throughput for the case of WLAN to UMTS handover, while Fig.7c and Fig.7d present the packet delay.

The measurement results reveal a serious problem regarding the WLAN/UMTS handover performance. As the WLAN is a local network and the UMTS is a global network, the handover suffers from a high communication-break period followed by a low performance period (named *slow start*) for the UMTS throughput. These periods are denoted as T_{break} and T_{slow} in Fig.7a. The described problem is not particularly related to the WLAN and UMTS networks. The very same problem will occur for every transition from a local to a global serving network (e.g. from

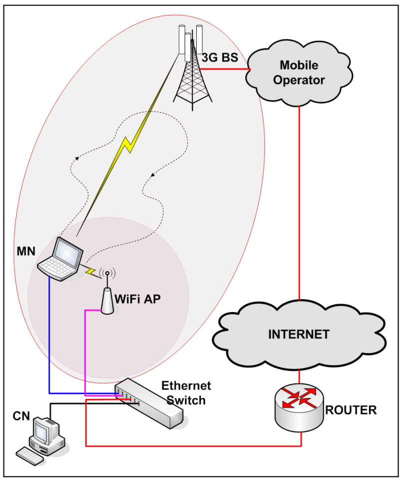

Figure 6: Testing scenario

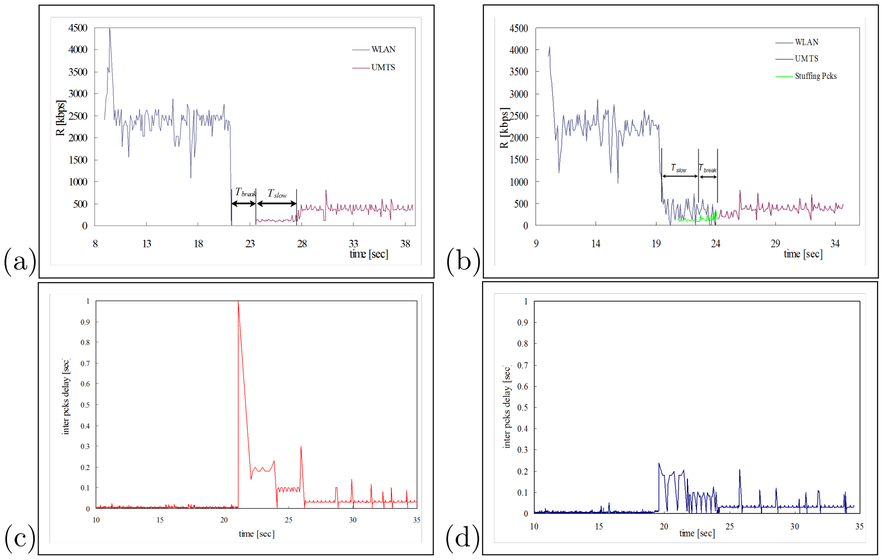

Figure 7: Handover performance: (a) Measured throughput before terminal upgrade, (b) Measured throughput after terminal upgrade, (c) Measured delay before terminal upgrade, (d) Measured delay after terminal upgrade

Ethernet to WLAN-based metropolitan network, from local WLAN to WiMAX network, from a terrestrial network to a satellite network, etc.). In order to overcome this problem, additional features are implemented in the terminal, enhancing the capabilities of its MIHF and NDIS sublayer.

4.3 Handover Prediction and Terminal Reconfiguration

The MIHF is extended with a *handover prediction* capabilities, whereas the NDIS sublayer is enhanced with additional reconfigurability control capabilities. The *linear predictor* implemented within the MIHF provides prediction of the near future WLAN received signal strength (RSS) values, presented by the RSS indicator (RSSI). The RSSI values $y_i, i = 1, 2, , N$ are measured at equally spaced time intervals. The predictor takes the last M RSSI values $y_i, i = 1, 2, .., M$ and predicts the following $(M + 1)$-th RSSI value. A stationarity is assumed, meaning that the autocorrelation function $R = y_j, y_k$ depends only on the difference $|jk|$ and not on the particular j and/or k values. Hence, the autocorrelation R has only single index and can be calculated as:

$$R_j = \langle y_j y_{i+j} \rangle \approx \frac{1}{N-j} \sum_{i=1}^{N-j} y_i y_{i+j} \tag{3}$$

Under the given assumptions, the estimation of the next RSSI value is:

$$\hat{y}_n = \sum_{j=1}^{M} d_j y_{n-j} + x_n \tag{4}$$

where d_j are linear prediction (LP) coefficients, obtained from the following set of M equations:

$$\sum_{j=1}^{M} R_{|j-k|} d_j = R_k, (k = 1, ..., M) \tag{5}$$

In (4), x_n is positive root of the mean square discrepancy $\langle x_n^2 \rangle$, estimated with the following equation:

$$\langle x_n^2 \rangle = R_0 - R_1 d_1 - R_2 d_2 - ... - R_M d_M \tag{6}$$

Based on this theoretical approach, the predictor can provide the MIHF with one predicted RSSI value $\hat{y}(t)$, based on the previous M received values:

$$\hat{y}(t) = f(y(t-1), y(t-2), .., y(t-M)) \tag{7}$$

For the prediction of the next RSSI values, the predicted output $\hat{y}(t)$ is used as a current input, coupled with $(n - 1)$ delayed measured RSSI samples to provide the next RSSI sample $\hat{y}(t + 1)$. This can be repeated N times, to predict the RSSI values sufficiently in advance:

$$\begin{aligned} &\hat{y}(t+N) = f(\hat{y}(t+N-1), \hat{y}(t+N-2), .., \hat{y}(t), \\ &y(t-1), y(t-2), .., y(t-M-N)) \end{aligned} \tag{8}$$

The prediction method is implemented within MIHF as a standalone procedure which requires two different parameters, i.e. the values of M and N.

The second enhancement of the architecture, i.e. the modification of the NDIS sublayer, involves introduction of two new operating modes: *mixed mode* and *stuffing mode*. When in mixed mode, each cycle of the Main Thread invokes the WriteHandler with interleaved interface handlers (WLAN and UMTS). This enables the MN to simultaneously send packets on WLAN and UMTS by switching. The stuffing mode is similar to the mixed mode, but the UMTS packets do not carry information bits. The mixed mode is used to overcome the T_{break} period by sending UMTS packets before the actual dropping of the WLAN signal. This compensates the initial delay introduced by the UMTS technology that results in the T_{break} period. The mixed mode needs to be activated T_{break}-time before the communication break. In addition, the stuffing mode should be introduced prior to the mixed mode in order to overcome the slow start of the UMTS network.

A total overcoming of the WLAN/UMTS handover problem requires a prediction of WLAN signal dropping for $T_{break} + T_{slow}$ time before its actual occurrence. The MIHF informs the RRM when predicting such situation. The RRM sends a command to the Main Thread to operate for T_{slow} seconds in stuffing mode and for the next T_{break} seconds in mixed mode. The network throughput in this case is depicted in Fig.7b). Regarding the inter-packet delay, the results show that the predictor implementation significantly improves the handover performance, resulting in seamless vertical handover and session continuity without a delay peak (see Fig.7d).

The WLAN throughput drops during the stuffing and mixed mode, but the communication continues seamlessly during the handover. It is important to note that the bitrates of WLAN and UMTS during the mixed period can be controlled according to the following analysis.

When only the WLAN interface is used for communication, the achieved interface capacity utilization (R_W) can be calculated as:

$$R_W = \frac{BS_W \cdot T_W}{BS_W \cdot T_W + TC} \tag{9}$$

where BSW represents the optimal burst size defined as the number of packets sent through the WLAN interface in one Main Thread cycle, T_W is the amount of time spent for sending single packet through the WLAN interface, and TC is the delay introduced by the Main Thread while checking all control information in single cycle. In the same manner, we can calculate the UMTS interface capacity utilization R_U for the period when only UMTS interface is used for communication (10), only this time we use the BS_U (optimal UMTS burst size) and T_U (UMTS packets sending time) parameters.

$$R_U = \frac{BS_U \cdot T_U}{BS_U \cdot T_U + TC} \tag{10}$$

During the mixed period the Main Thread uses both interfaces for communication in one cycle. Consequently the interface capacity utilization is different and can be calculated as:

$$R_{WM} = \frac{BS_{WM} \cdot T_W}{BS_{WM} \cdot T_W + BS_{UM} \cdot T_U + TC} \tag{11}$$

$$R_{UM} = \frac{BS_{UM} \cdot T_U}{BS_{UM} \cdot T_U + BS_{WM} \cdot T_W + TC} \tag{12}$$

where BS_{WM} and BS_{UM} represent the values of the burst size for WLAN and UMTS during the mixed period, respectively. By changing the BS_{WM} and BS_{UM} parameters as independent variables, the R_{WM} and R_{UM} can be controlled within the following boundaries:

$$\frac{T_W}{T_W + BS_{UM} \cdot T_U + TC} \leq R_{WM} \leq \frac{BS_{WM} \cdot T_W}{BS_{WM} \cdot T_W + T_U + TC} \tag{13}$$

$$\frac{T_U}{BS_{WM} \cdot T_W + T_U + TC} \leq R_{UM} \leq \frac{BS_{UM} \cdot T_U}{T_W + BS_{UM} \cdot T_U + TC} \tag{14}$$

The results presented in Fig.7b and Fig.7d use $BS_{WM} = BS_{UM} = 1$. The results show that the implementation of handover predictor and terminal reconfiguration (i.e. the introduction of mixed and stuffing modes) successfully overcomes the problems related to MN's transition from a local to a global serving network.

5 Conclusions and Future Works

The concept of reconfigurable interoperability becomes a cornerstone of future communication systems under heterogeneous access scenarios. The ability to choose among different access networks with user transparent and seamless vertical handovers and the ability to reconfigure and sustain the required QoS levels is a quintessential aspect of the development towards modern communications.

The emerging IEEE 802.21 standard represents a promising effort in this direction aiming at provisioning a global standard for media independent handovers. This paper shows the quantitative benefits and the corresponding potentials of the standard, providing case studies involving simulation and demo-testing platforms. The simulations have proved that the introduction of IEEE 802.21 exhibits lower vertical handover latency values for all analyzed scenarios. Furthermore, the results revealed that the proposed platform that combines IEEE 802.21 standard and intelligent resource management outperforms the SNR based serving policies and especially when the scenario involves low number of mobile users. Finally, the paper presented a reconfigurable terminal prototype, which is capable of signal prediction, fast interface switching, combined transmission, etc. The future of communications will bring intelligent devices which should be able to combine different data flows coming from different communication technologies with high rates, while allowing the user to freely traverse through heterogeneous environments with high speeds.

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