WF – A RECONFIGURABLE RADIO SYSTEM ON THE PATH TO SDR

Hanna Bogucka (Poznan University of Technology, Institute of Electronics and Telecommunication, Poznan, POLAND, email: hbogucka@et.put.poznan.pl);
Andreas Polydoros (University of Athens, Electronics Laboratory, Division of Applied Physics, Department of Physics, Athens, GREECE, email: apolydor@cc.uoa.gr);
Giuseppe Razzano (University of Rome "La Sapienza", INFOCOM Dpt., Rome, ITALY, email: razzano@infocom.uniroma1.it)
Luigi Agarossi (Philips Research Monza, Monza, ITALY, email: luigi.agarossi@philips.com)

ABSTRACT

In this paper, some key aspects of the 5th Framework IST EU Project WINDFLEX (WF) [1] are presented, in particular, those that pertain to its flexibility, adaptivity and reconfigurability features. The interpretation of Quality of Service (QoS) in this WF system is provided, and some examples of system-level, high-QoS provision tools are discussed. The WF evolution perspective is presented, and its relation to the SDR concept is studied.

1. INTRODUCTION

In recent years, the design of reconfigurable modems for mobile communication applications has been a subject of intensive research and development, motivated by increasing user demands for mobile-terminal flexibility, multi-functionality, multi-modality and scalability. In parallel with the end goal of the *Software Defined Radio* (SDR) concept, some intermediate solutions for such reconfigurable systems and components have been studied. Apart from these studies, another direction of research in this area is visible, a trend to develop intelligent, autonomous, self-organizing reconfigurable terminals, which learn the environment and optimize their operation accordingly. In this paper, we present some key aspects of the 5th Framework IST EU project WF [1] (Wireless INDoor FLEXible High Bit-rate Modem Architectures) and, in particular, those that pertain to its Flexibility, Adaptivity and Reconfigurability (FAR) features, since *identification* and *implementation* of these FAR features have been perceived as crucial project goals; similar features also appear as major goals of SDR.

WF is an OFDM-based waveform architecture employing certain novel techniques, meant for indoor applications, and in particular *ad hoc* networking devices. This paper focuses on those FAR features which define, negotiate and assure provision of the required Quality of Service (QoS) and the associated operational efficiency in challenging environments, but also encompass a wider range of potential system capabilities needed to meet future demands. This results in a design philosophy that envisions WF as an evolving, autonomous, intelligent radio system technology, and foresees its evolution possibly to take up some challenges of the SDR concept or to become its alternative.

Here, we study the feasibility of various WF concepts and directions. We define and quantify the metrics, especially those of the QoS framework, which must be satisfied at each stage of the WF evolution. We also describe key aspects of the system optimization, point out major analytical difficulties that it entails in present manifestations, and present examples of system flexibility. Finally, we summarize the relationship between the WF evolutionary directions, and the broad SDR concept.

2. THE FAR CONCEPT

FAR, as previously defined, stands for Flexible, Adaptive and Reconfigurable, properties that are desirable in general of wireless terminals and systems. Each of these concepts has been previously examined in the broad area of wireless (radio, mostly) systems and networks, occasionally with overlapping meanings and notions. In this section we provide some definitions, clarifications and further elaboration of these concepts (an answer to the "what" question), explain the reasons for employing them (the "why") and, finally, show manifestations of these concepts in wireless, indoor, *ad hoc*, run-time flexible terminals and systems (the "how" aspect). Much of the related discourse can be found in the broad research areas of "reconfigurable systems and terminals", "flexible radio", "software-defined radio", and such. A thorough taxonomy of the field would require sorting out concepts like "system", "architecture", "structure", "design", "configuration", "reconfigurability", "flexibility", "adaptivity", "reprogrammability", "modularity", "scalability", etc. Here, for the sake of compactness, we propose the following terminology: The central notion of *flexibility* is defined as an "umbrella" concept, encompassing a set of independently occurring (design) features, such as *adaptivity*, *reconfigurability*, *modularity*, etc., such that the presence of a subset of those would suffice to attribute the qualifying term flexible to any particular system. These features are termed "independent" in the sense that the occurrence of any particular one does not predicate or force the occurrence of any other. For example, an adaptive system may or may not be reconfigurable; and so on. It may be desirable later to include in the definition additional concepts such as "ease of use", or "seamlessly operating from the user's standpoint" into the broader notion of flexibility, and this can happen as long as these attributes can be quantified and identified in a straightforward way, adding a new and independent dimension of flexibility. Here we define *a system to be* *adaptive* *if it can respond to changes by properly altering the numerical value of a set of parameters. It is* *reconfigurable* *if it can be rearranged, at a "structural" or "architectural" level, by a non-quantifiable change in its configuration;* "non-quantifiable" means that it cannot be represented by a numerical change in a parametric set. For example, the "structural" change of going from a serially-concatenated turbo code to a parallel-concatenated turbo code cannot be represented by a change in a numerical quantity. Similarly, the "architectural" change of replacing the hardware (HW) implementation of the IF stage by digitization and software-controlled processing, as in pure software-defined radio, cannot be represented by a numeric change. Clearly, certain potential changes may fall in a gray area between definitions. For instance, changing the number of sub-carriers in an OFDM system may appear as an "adaptive" change (it is quantifiable), but if it has structural implications at the FFT and other levels, it may also be considered a structurally reconfigurable type of change.

Why is flexibility a desirable characteristic of such a radio system? A simple answer resides in the general desire to be able to respond to various changes in the requirements or the specifications (present or future). These can be *service (*or *user) requirements* and their related attributes (data rates, QoS, latency constraints, security, network accessibility, etc.), *network-level requirements* (e.g., efficient recourse allocation), *"environmental*" *conditions* (e.g., system dynamics, channel changes, mobility, other user-interference, other-system interference, etc.), or *system-level conditions*, driven by the requirements of the network operator, and/or service provider, and/or manufacturer: operation within multiple standards or services or modes, future-proofness, seemlessness across systems (say, indoor/outdoor operation) and the like. The *user*, the *system* and the *channel* are the three actors that affect the general operation, and they can affect it each independently. Flexibility is thus the toolbox that enables the accommodation of any such circumstances, and therefore comprises a set of techniques in the service of the desirable systemic properties of *efficiency* (spectral utilization), *reliability* (robustness), and *scalability*.

In order to make business sense, flexibility must accrue benefits that outweigh potential minuses in cost, weight, power dissipation, etc.; flexibility and efficiency are sometimes contradictory notions (e.g., DSP's are known to be more flexible than ASIC's but less power-efficient). A careful analysis is needed to *establish measures of goodness* of the flexible design, namely an agreeable set of Figures of Merit (FoM). Typical FoM's can be: Transmission power, processing power, weight and size, user friendliness (as in the case of software (SW) downloads), and so on. A typical and popular optimizable FoM within the framework of flexibility is minimization of the total power of a flexible modem for a negotiated level of service. Power consumption, for instance, has been the subject of optimization in a WF modem as well as other designs. The "adaptivity toolbox" for achieving such includes a set of transmitter parameters that can be altered in, say, an OFDM air interface, as well advanced signal processing on the receiver side, including adaptive algorithms for reliable signal reception. Similarly, the "reconfigurability toolbox" for such an optimization may include rearrangement of some blocks to limit their processing power, possibly in response to a lower required link bit rate, or any "on-off" type of reconfiguration, like turning off some functional blocks of a modem, e.g. equalizer adaptivity or coding, when the channel conditions still allow for acceptable quality of data reception. Also at the network level, reconfiguration is granted to ensure the capability of reacting to changes in the network topology.

It is typically required to introduce new architectural elements in flexible modems, namely sub-systems which can perform such optimization procedures in real time or non-real time (depending on the application), and one such element is the *supervisor (coordinator, HW/SW manager* being similar terms). Such a supervisor (SPV) plays a dominant role in the WF modem base-band (BB) architecture presented in Fig.1. It coordinates operation of all adaptive and reconfigurable blocks. Based on the input from the higher layers and the channel knowledge, it generates optimized directives and parametric values to the appropriate reconfigurable and adaptive functional blocks of the modem, according to a specially designed inference algorithm. Developing the optimal inference algorithm for the SPV is a challenging task, specially for a turbo-coded OFDM system like WF, which may operate in an unpredictable radio environment.

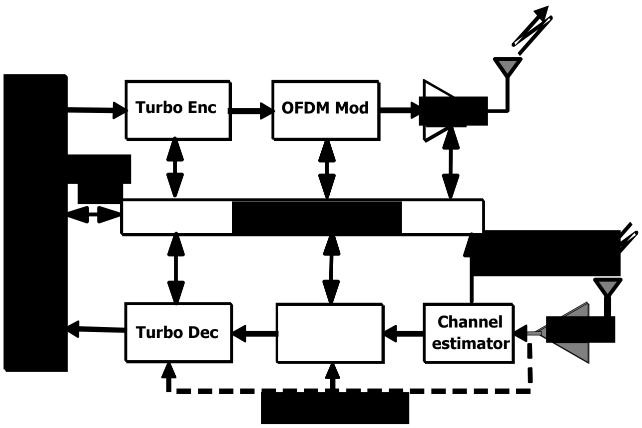

Figure 1. The WF base-band architecture

Definition	QoS layer	Mechanisms
User satisfaction	Applications	User profile, application adaptation
QoS core	Network	QoS signaling, capacity, admission control
Protocol performance	Data link	Scheduling, bandwidth, weighted dropping,…

Figure 2. QoS layers, definitions and support mechanisms [2].

3. ON THE MEANING OF QoS IN WF

The *ad hoc* nature of the network under consideration poses numerous challenges that must be overcome in order for the network to benefit the most, prime between which is the QoS issue. In view of technical difficulties, such as the lack of fixed infrastructure (e.g., base stations), mobility of the network nodes, limited bandwidth, and the inevitable constraints of a radio channel, QoS maintenance is arguably a demanding and problematic task in *ad hoc* wireless networks. Currently, these networks use the *best effort* philosophy to provide the required QoS for a particular user. This means that a network "does its best" to transport user data packets with the requested speed and performance level, but without any fixed guarantee. Recently however, *guaranteed* QoS provision in wireless networks emerges a subject of growing interest.

The meaning of QoS in wireless networks, in general, is the degree of goodness, to which the set of service requirements are fulfilled by the system (one of the three actors affecting general network operation, as mentioned in the previous section). These requirements manifest themselves via a number of quantifiable attributes, such as required bandwidth, bit rate, bit- and packet-error rate, etc., as well as non-quantifiable ones. However some of its attributes cannot be easily measured because QoS pertains to multiple OSI layers. In fact, QoS requirements and their attributes are usually defined differently for the various layers.

The QoS concept is associated with a three-layered stack which eliminates some of the OSI layers. The defined QoS layers encompass: the application, networking and data link layer [2]. The simplified definitions of the QoS and mechanisms which support QoS at all these layers are presented in Fig. 2.

At the application layer, the main determinant of the QoS is the user satisfaction, which is also the ultimate criterion of the overall network goodness. It is not easily measurable, because it depends on the user individual expectations and perception. Therefore the right tool to assess user satisfaction is subjective testing, i.e. interviewing a representative group of users. Typically, users expect to experience a certain confidence about the anticipated level of network and application accessibility. High network accessibility means easy access to a network at a low probability of lost or blocked calls, as well as the possibility and the ease of seemless operation in many contemporary and future network standards (future-proofness). Application accessibility aims at the provision of the required application along with the particular user preferences pertaining to it, such as transmission reliability and security.

The subjective nature of the QoS at the application layer implies the main mechanism to maintain it, i.e. service adaptation pertaining to a general flexibility of a network. Starting a new connection, a user must pre-define the requirements and acceptable tolerance for the QoS. Typically, at this stage, a user negotiates demanded service quality with a system. If a system is unable to provide it, it may simply notify a user about it and reject the service, or it may suggest service provision with lower quality. The user is usually needed to maintain an active feedback during negotiations.

The network layer for the QoS is defined as a core QoS layer that handles mediation between the application and data link layers. Its main objective is to translate user requirements to service parameters, which form a set of easily quantifiable metrics. The mechanisms serving this major goal involve QoS control (including access control) and signaling. A typical admission control algorithm would first check (by asking lower layers) if an unloaded network can satisfy user requirements. If so, there can be two strategies to secure the requested QoS, namely providing either soft or hard guarantees, respectively. According to the soft guarantee strategy, a service invocation is always accepted, and the requested service is handled by the network, conformably with the best-effort philosophy. The hard guarantee strategy involves a new connection setup with all necessary signaling. Basically, a user can access a network, and the requested QoS can be provided only if a new connection does not imperil the other, already guaranteed connections [3].

The meaning of the QoS at the data link layer is the protocol performance, which is specified explicitly by parameters, such as delay, delay variance and packet loss probability. Here, the mechanisms to provide the required service quality involve effective management of network resources, mainly frequency and time resources. The appropriate allocation of frequency bandwidth and time slots encompass intelligent packet switching, scheduling and weighted packet dropping.

Finally, at the physical layer, which is not depicted in Fig. 2, the rest of the user requirements concerning network and application accessibility are satisfied to some degree, resulting in a certain QoS. The transmission parameters, such as: modulation size, code rate, radiated power, number of used subcarriers (in OFDM-based systems) are chosen to provide the requested bit rate and bit error rate. Note that notions pertaining to user requirements should not be confused with those pertaining to QoS. User requirements for network and application accessibility are usually pre-defined by the user during the negotiation stage for a new connection. They can be represented by metrics, e.g. the transmission bit rate and bit error rate. Thus, after the new-connection negotiation phase, they comprise a set of requirements which should be satisfied with the best effort involved, or with a hard guarantee. In the latter case, some additional metrics must be pre-determined, e.g. the variance of bit error rate, its maximum temporal value, or the time over which it is estimated. These metrics cannot be a subject of optimization, since they are an input request from a user.

Network and link optimization concepts relate to all the parameters which pertain to general cost function, such as the transmit power, power needed for BB processing, size and weight of a terminal, billing, etc. Hence, the FAR concept in WF is meant not only to provide the QoS and meet its ultimate criterion, namely user satisfaction, but also to achieve this goal at a minimal possible cost (whichever way this is defined). Flexibility is not costless, but in view of the advantages described in the previous section, many users would potentially accept it, and consider it to be worth the price. In the next two sections we present some interesting examples of FAR as considered for implementation in WF at the physical (PHY) and medium access control (MAC) layers.

All these issues of the QoS in *ad hoc* networks discussed above remain essential for WF. Because WF is a single-hop network, where packets are transported directly from a source node to a destination node, there is no complicated packet and QoS routing. The packet delay variations (delay jitter) are particularly small in WF cluster, thanks to the innovative design of a scheduler.

4. THE RECONFIGURABLE WF BASE-BAND ARCHITECTURE

The WF flexible modem architecture is designed to minimize the power consumption of user equipment. Both flexibility tools are exploited, namely adaptivity and reconfigurability, in order to achieve this goal. As far as its baseband operation at the physical layer is concerned, the following set of adaptive transmission parameters are adjustable, and hence the subjects of optimization:

1. modulation size
2. code rate (for a fixed code)
3. code block size
4. transmission power
5. number of active sub-carriers after excision of the deeply attenuated, i.e. “useless” ones, in the *Weak SubCarrier Excision* (WSCE) algorithm.

The main optimization criterion for the choice of the modulation size, code rate and code block size is to provide the requested bit rate and bit error rate with the minimum radiated power. On the receiver side, advanced signal processing includes adaptive algorithms for equalization, phase noise/residual frequency offset compensation, iterative decoding (potentially, with an adaptive stoppage time for iterations), etc.

The following examples of baseband reconfiguration are candidates in the OFDM WF design:

1. altering the number of useful sub-carriers (after excision of the “weak” ones) within a fixed channel bandwidth, in response to a change of the required bit rate;
2. “on-off” type of reconfiguration, e.g., turning off the adaptivity in the equalizer when the channel characteristics are static;
3. adjustable type of code application (uncoded, convolutional code, turbo code), depending on channel conditions;

Let us note that reconfiguration of the WF baseband structural blocks is driven by channel changes or by user requests. It may also take place while the modem turns from one state of activity to another, namely form the *active*, *idle* or *off* mode to another one of those.

5. THE WF MASTER-SLAVE CLUSTER ARCHITECTURE

Within a WF network [1], the Cluster is a set of devices such that any couple of them can establish a direct connection to exchange user data. Packets are directly transmitted from the source to the destination device (without any “relay” or “base” station) according to the single-hop full-meshed structure of the network.

Within a cluster a device called “Master” owns the coordination role, and dynamically decides the resources assignment on the basis of traffic conditions. All the other devices in the Cluster act as “Slaves”. There are no hardware or software differences among the devices, the Soft Master Handover (SMH) mechanism guarantees that the Master role is always played by the device which is in the “best” position within the cluster [4]. This requirement is a crucial issue for the whole system. In fact, if the Master device is not correctly received by all the slaves associated to the Cluster, no coordination can be granted, resulting in a big degradation of the overall performance.

5.1. The Soft Master Handover

The SMH mechanism allows to reconfigure dynamically the Wireless LAN, ensuring the capability of reacting to changes in the network topology, but at the same time introducing a low level of overhead, due to the control information. SMH denotes the set of procedures and protocols implementing the choice and the passing of the Master among the devices. It is based on the Master Election Procedure (MEP) and on the Master Passing Protocol (MPP).

MEP is the procedure for the election of the new Master. It is performed by the current Master every period Δ, and also whenever it detects that the current cluster topology is changed, due to a new device that is associated with the network or a device that is switched off. The procedure is carried out through the following steps:

1. The Master monitors and stores a list of parameters regarding the quality of the links between all the devices of the Cluster.
2. The current Master runs the Master Election Algorithm, selecting as Master the device which satisfies a given optimality criterion.
3. Whenever the current Master is confirmed as new Master, the MEP ends. Otherwise, the current Master passes its role by running the Master Passing Protocol.

The old Master carries out the following steps:

1. It informs the new Master about its election. The new Master starts to listen the broadcast packets, so as to collect the information needed to perform the Master functionality.
2. It sends to the new Master some reduced information about cluster and connection management.
3. Finally, it decrees the definitive passing of the Master functionality to the new Master, which starts to transmit the Synchronization packet and to carry out the other Master functionalities.

6. ON THE RELATION OF WF TO SDR

The WF reconfigurable modem and system design [1], which encompasses multiple architectural and optimization novelties, can be envisioned as an intelligent radio system technology, autonomously evolving towards a broader concept. The general philosophy of WF design allows for predicting the following two potential directions of evolution.

First is a WF modem which ensures operational efficiency in challenging (dynamic, multipath) radio channels, one which demands real-time operation, environment adaptivity, and modem reconfigurability which serve useful metrics such as power efficiency, as well as any other well-defined quantifiable metrics. Its architecture is built around a centralized SPV, which has intelligence to learn the environment and optimize system operation to provide high quality of service requested by a user. The working paradigm in this direction is "efficiency of operation". It also describes the current phase of the WF concept, in which the FAR features support high quality of service and efficient, low-cost operation [5]. Evolution of WF in this direction tends to an autonomous, self-intelligent and self-configuring modem design, divergent from the SDR philosophy of a downloadable terminal.

The second direction is a WF modem which tends towards a multi-service, multi-standard operation, one that has the potential to reconfigure in a way that can encompass more standards, not only those based on OFDM. Such a WF system would employ optimized hardware platforms and SW download capabilities. In this case, the FAR features are tools for avoiding bulky multi-mode, multi-standard terminals. They would assure the "ease of use" and "seamless operation", which are also major paradigms for the SDR. This is a long-term vision of WF as a more universal machine that generalizes its current reconfigurability features. Its architecture would also be more general one with a centralized SPV that handles many flexibility-related tasks. Software downloadability would increase terminal flexibility pertaining to its multi-standard operation. A necessary SW could be downloaded for a successful terminal login to a certain network standard. On the other hand, SPV would assure its environmental adaptivity and optimized operation within this particular network. Such an architecture would purport to address many past, present and foreseeable systems, and could even propose it's own universal waveform-coding basis that could allow a description of any imaginable air-interface radio waveform. Let us note that this long-term vision of WF evolution converges to the SDR concept, since software radio is most commonly defined as an emerging technology, thought of as building general flexible radio systems, multi-service, multi-standard, multi-band, reconfigurable and reprogrammable by software [6].

The relation of WF phases presented above to SDR can be summarized by indicating how far or how close the main features of SDR (multi-service, multi-standard, multi-band, reconfigurability and reprogrammability) are approached by these phases. In Table 1 such an outline is given.

Here, we address some important issues, such as: main goals, technological difficulties, architectural solutions and SW download, related to the WF evolutionary phases and SDR. The technical targets of SDR mainly encompass: SW implementation of totally digital base-band (BB), intermediate-frequency (IF) and possibly radio-frequency (RF) parts of a terminal, and replacement of ASIC technology with DSP engines (FPGA or digital signal processors)[7]. In general, they should be accomplished to assure multi-standard operation, which is the main goal of the SDR concept. For both WF phases, the main goal is to optimize transmission and overall system according to general criteria: high QoS (enveloping high system effectiveness) and low cost (mostly power consumption). Additionally, WF II may adopt some of the SDR targets.

The well-known technological difficulties of SDR in its terminal-IF and RF parts are not issues for WF which has these parts fully analog (traditional super-heterodyne). The WF technological difficulties appear in the BB, and are of the same nature as for SDR. These basic problems are: provision of enough processing power to allow real-time operation, minimization of power consumption, assurance of HW functionality required for fast signal processing, minimization of circuit complexity, reduction of terminal and system cost, and transceiver dimensions.

The architecture of WF terminal is presented in Fig. 1. It corresponds to a specialized microcomputer, operated by a central intelligence, such as the supervisor. It is not fully programmable structure, in the current phase of WF. WF I architectural evolution would involve SPV design and development to a very intelligent, cognitive, environment-aware and self-adjustable radio.

Evolution in a direction of WF II will require a more universal, reprogrammable architecture, with very sophisticated SPV algorithms, possibly downloadable, providing detailed instructions for adaptive and reconfigurable sub-systems of a transceiver able to operate under various standards. The appropriate procedures addressed by the SPV may permanently reside in the memory or be downloaded from a smart card or via air interface. Such an architecture, when optimized, would assure fulfilling requirements stated for a flexible system, its future proofness, and possibility to upgrade its software.

Finally, let us emphasize that the HW platform for a reconfigurable transceiver, such as WF, plays a dominant role in its efficiency to reconfigure, including reconfiguration time, and thus, needs to be carefully designed. The current WF demonstrator platform is based on FPGA. In the future, probably some fusion of programmable and reprogrammable logic like: FPGA, general-purpose and special-purpose DSPs may be necessary.

Table 1. Summary of key features of WF evolutionary directions

WF I - *"efficiency of operation"*	WF II - *"seemless operation"*	SDR *"universal machine"*
Multiservice (services meant for WF I)	Multiservice	Multiservice
One or just a few standards in the same frequency band and OFDM-based standards	Many standards (possibly not all)	Multistandard
One band	Wide range of bands	Multiband
SW/HW-implemented FAR features	SW/HW-implemented FAR features, SW download	SW reprogrammability

7. REFERENCES

[1] WINDFLEX White Paper, http://www.vtt.fi/ele/research/els/projects/windflex.htm

[2] J. Mikkonen, "Quality of Service in Radio Acess Networks", Doctoral Thesis, Tampere University of Technology Publications, Tampere 1999

[3] S. Chakrabarti, A. Mishra, "QoS Issues in Ad Hoc Wireless Networks", *IEEE Commun. Magazine*, vol.39, pp.142-148, Feb. 2001.

[4] R. Cusani, F. Delli Priscoli, G. Ferrari, G. Razzano, M. Torregiani, "Dynamic, channel status driven, reconfigurable Medium Access Control for the WIND-FLEX Wireless Local Area Network", Proceeding of IST Mobile Summit 2001 (Barcelona, Spain), pp. 375-380.

[5] I. Saarinen, et al. "High Bit Rate Adaptive WIND-FLEX Modem Architecture for Wireless Ad-Hoc Networking in Indoor Environments", IST Mobile Summit'02, June 16-19, 2002, Thessaloniki, Greece.

[6] E. Buracchini, "The Software Radio Concept", *IEEE Commun. Magazine*, vol. 38, pp.138-143, Sept. 2000

[7] J. Mitola, *Software Radio Architecture*, Wiley-Interscience Publication, New York, 2000