Paper

Adaptive Resource Management and Flexible Radios for WiMAX

José Salazar, Ismael Gómez, and Antoni Gelonch

Abstract—The availability of dynamic resource management will be crucial for the deployment of future wireless systems characterized by high data rate services with rigid quality of service demands. Flexible radios appear as the technological answer required to achieve constraint goals under different channel conditions and transmission scenarios. This paper is focused on enhancing another step of flexibility within the resource management by including an efficient handling of computing resources. This concept towards flexible architectures represents a key word for a real successful implementation due to the relationship between the radio applications, which face the scarcity of resources within a heterogeneous environment, and the processing power needed to execute them.

Keywords—computing resource management, radio resource management, reconfigurability, software radio platforms.

1. Introduction

Some important threads for new wireless technologies such as long term evolution (LTE) and worldwide interoperability for microwave access (WiMAX) mobile (802.16e standard) are high demands of flexibility, and reliability. These future mobile networks are defined by several radio access technologies (RAT's) with cells in different hierarchical levels and frequencies offering the same or nearly the same services [1]. For multistandard/multimode terminals the preference of one standard over another will be defined by different criteria. For example required quality of service (QoS), link conditions, or network traffic; but could also be dictated taking into account the terminal capabilities such as battery life and energy consumption.

Concerning the deployment of radio interfaces of both terminals and base stations becomes a hazardous task to obtain solutions where are considered all the possible scenarios, and parameters. Different scenarios for instance, imply that the assignment of services and its quality restrictions will depend on the user preferences and capabilities, or could take part as a seamless roaming depending on the area of location. However, a reconfiguration process is inherited and this will be dictated by a set of parameter selection towards an optimization target.

Software radio (SR) exploits reconfigurability and adaptive parameterization to achieve flexibility [2], [3]. Adaptive parameterization means that the signal processing structure may be switched by parameters to realize different standards. Nevertheless, the reconfigurable capacity of a SR platform rely on the processing computational resources consumed by the standards is able to execute [4]. Flexible radio systems which can be able to dynamically establish an optimal management of resources of SR platforms will play a main role. The idea behind this work is a framework which brings together a dynamic awareness and control of the resources involved in the reconfiguration process. The goal in this paper is to test a fair usage of resources across radio and hardware environments, focused on trading efficient computational and radio resource assignation but providing constant QoS.

The rest of this paper is organized as follows: Section 2 deals with the concepts of advanced resource management and orthogonal frequency division multiplexing (OFDM) systems. Section 3 describes a framework for flexible radio platform. Section 4 describes a case of study defining system specifications adopted for simulations. Follows simulation results and discussion in Section 5. Finally, Section 6 concludes the paper.

2. Advanced Resource Management and OFDM

2.1. Radio Resource Management

The scenario in modern mobile networks introduce new tasks within the radio resource management (RRM) problematic, an efficient use of radio resources is determined by the general characteristics of the networks their selves and by a common management within the whole system. Reconfigurable baseband RF/IF platforms include the use of advance media access control (MAC) and RRM functionalities. Such solutions incorporate suitable control of the reconfiguration process necessary to assure the selection of the RAT which can offer the desired service [1], they manage dynamically the allocation and de-allocation of radio resources (e.g., time slots, codes, frequency carriers, etc.) [5]. On the other hand in order to achieve vertical and horizontal handovers, radios with cognitive centric properties, such as spectrum monitoring, localization, tracking, and others features [1], appear to handle necessary cross-layer interactions leading to increase multiuser capacities.

2.2. Computing Resource Management

Hardware platforms on the mobile devices will impose limits on processing operation even under optimization processes of cognitive algorithms. Therefore for a more sustainable approach another feature must be added: the awareness of the processing capabilities, this is a real way towards flexibility and granularity. The management of computing resources refers to the hardware that implements the (software-defined) signal processing chains for radio communications.

2.3. Adaptive Modulation in OFDM-Based Systems

Orthogonal frequency division multiplexing systems are conceived for data transmission in frequency selective channels, and have as mathematical background the fast Fourier transform (FFT). OFDM advantages are spectral efficiency, ability to fight multipath distortion and delay spread, and resilience to intersymbol interference (ISI). Adaptive modulation in OFDM entails some decision taking about the service data rate, bandwidth of transmission, by selecting some transmission mode. It presents several advantages compared to techniques that use a unique carrier signal. Based on the channel prediction the transmitter selects the appropriate modulation schemes for next time slot. The constant throughput of an adaptive OFDM scheme exploits the frequency selectivity of the channel while offering a constant throughput [6]. Higher order modulation schemes, which are spatially more efficient such as quadrature amplitude modulation (QAM), need better channel conditions that the lower order modulation schemes accordingly to a bit error rate (BER) criterion.

2.4. The 802.16e Standard (WiMAX Mobile)

The IEEE 802.16e standard release defines the WiMAX mobile system. WiMAX is short of worldwide interoperability for microwave access officially known as wireless metropolitan area network (MAN) [7], [8]. Quality of service in WiMAX is delivered using adaptive modulation and variable forward error correction (FEC) encoding per RF burst.

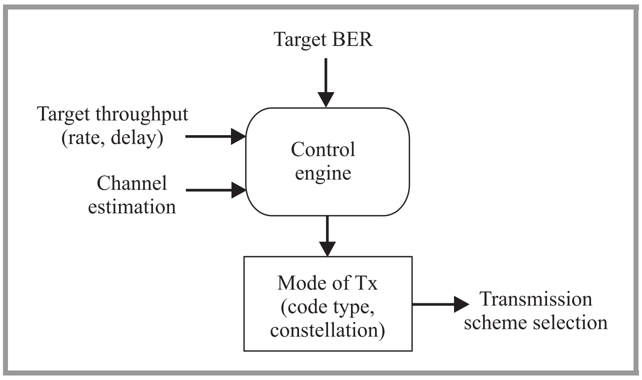

Fig. 1. Algorithm for adaptive modulation in WiMAX.

The transmission modes are defined by the MAC layer in order to adjust the user quality of service parameters depending on the channel characteristics, such as the delay spread, the fading, the user speed, etc. This ensures a robust link while maximizing the number of bits/second for each user unit, i.e., enables an optimal average data rate, improving system capacity and also allow being able to deal with service level agreements [9]. Switching levels for modulations schemes are set to achieve some BER performance, so that if the estimated channel condition is within the stored switching level for the modulation scheme under operation it maintain the same modulation format [10], [11].
The algorithm is shown in Fig. 1. Evaluates the channel, the required throughput to achieve the target BER, and switch the transmission mode, if the channel conditions (signal-to-noise ratio – SNR) are below some threshold, then renegotiation of target QoS takes place.

3. Integrated Resource Management Framework

Adaptive modulation for WiMAX accomplish to have self awareness deciding about the data rate, the transmission mode, and therefore about the bandwidth of the transmission. Nevertheless, some selections might be achieved to support the user's required QoS, or the network load, at the expenses of rising computational load and inefficient energy consumption. For example, let suppose a scenario where a user of a certain service will require certain BER $> 10^{-4}$ then considering the link conditions, a more efficient spectral scheme shall be selected such 64 QAM; nevertheless such terminal has limited computing resources, or less battery life in order to execute the signal processing tasks, so that the system capacity will be affected. Conservative approaches, tending to reduce sustainable rate through negotiation, or even not taking into account QoS constraints, will maximize radio capacity at the expenses of computing costs.
Trade-offs between capacity, robustness and computing capabilities might be accomplished in real time. The concept of flexible radios introduces automated radio, com-

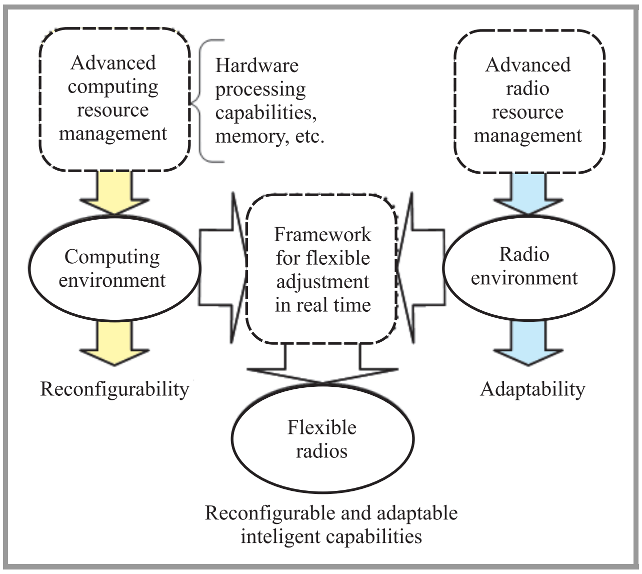

Fig. 2. Flexible radio framework.

puting and energy resource management of the SR equipment. Flexible radios ease an exchange of radio for computing resources and vice versa [4]. Parameterization might be achieved by learning standards and its features, i.e., defining the similarities and dissimilarities among their signal processing chains [3], thus aassembling platform-specific, defining the parameters dependencies of the different modular blocks of a communications standard chain, including the computational costs (million instructions per second/million operations per second (MIPS/MOPS) counts).

In the framework depicted in Fig. 2, an engine based on dynamic wave-form design, continuously seek the best set of resources available, taking decisions for parameter optimization maintaining QoS, based on radio, and computing environments monitoring and even future predictions of behaviors. This dynamic wave-form-design varies from the adaptive modulation process described before because the parameter changing depends on feedback information searching a fair distribution on resources utilization across radio, hardware and application environments.

4. Case Study

4.1. The IEEE 802.16e System Model

As an OFDM system, the high data rate sequence of symbols is divided into multiple parallel low data-rate sequences, each of is used to modulate the orthogonal subcarrier. The transmitted baseband signal can be represented as

$$x(t) = \sum_{i=1}^{L-1} s[i] \cdot \mathrm{e}^{-\mathrm{j}2\pi(\Delta f + iB_c)t},\ 0 \le t \le T,$$

where: $s[i]$ is transmitted symbol of the ith subcarrier, L – total number of subcarriers, B_c – subcarrier bandwidth, Δf – frequency offset, T – useful symbol duration (without cyclix prefix).

Table 1
Parameters for OFDM symbols

Parameter	Value	Definition
B	1.25, 1.75, 5, 10, 15	Channel bandwidth (adjustable) [MHz]
L	128, 512, 1024, 2048	Total number of subcarriers, including the user subcarriers N_S, guard subcarriers N_G and pilot subcarriers N_P, normally is equal to the FFT length (N_{FFT})
n	28/25	Oversampling factor
G	1/4, 1/8, 1/16, 1/32	Ratio of cyclic prefix time to useful time

At the receiver, the symbol $s[i]$ is calculated integrating the received signal with a complex conjugate of the corresponding subcarrier:

$$\widehat{s}[i] = \int_0^T x(t) \cdot \mathrm{e}^{\mathrm{j}2\pi(\Delta f + iB_c)t}\,\mathrm{d}t.$$

As it was described in Section 2, WiMAX physical layer allows making an optimum choice of various parameters, such as prefix cycle length, number of subcarriers, subcarrier spacing, preamble interval, in order to achieve some performance goal. The respective values defined for the primitives of an OFDM symbol are condensed in Table 1 [6].

Based on these parameters the time duration of an OFDM symbol T_s and thus the corresponding data rate R can be acquired as it follows:

$$T_s = (1/\Delta f)\,(1+G),$$

$$T_s = [1/(f_s/N_{FFT})]\,(1+G),$$

$$T_s = [1/(nB/N_{FFT})]\,(1+G),$$

$$R = \frac{N_s N_b C_{rate}}{\frac{N_{FFT}}{nB}\,(1+G)},$$

where N_b, C_{rate} are the transmission parameters; C_{rate} is coding rate used, N_b is number of bits, depending on the constellation used.

4.2. Performance of the IEEE 802.16e Physical Layer

WiMAX physical layer advantages depend significantly from the timing, and frequency synchronization at the receiver side which is achieved by the using of pilots and the cyclic prefix insertion [6], [12]. BER coding and modulation schemes listed in Table 2 have been evaluated using Monte-Carlo simulations developed in MATLAB.

Table 2
Simulated coded and modulation schemes

Scheme	Modulation	RS code	Conv. code
1	QPSK	(32, 24, 4)	2/3
2	QPSK	(40, 36, 2)	5/6
3	16 QAM	(64, 48, 8)	2/3
4	16 QAM	(80, 72, 4)	5/6
5	64 QAM	(108, 96, 6)	3/4
6	64 QAM	(120, 108, 46)	5/6

4.3. WiMAX Computational Complexity

Another advantage of OFDM to single-carrier modulation schemes is that it requires lower computing costs for higher data rate links.

Typical equalizers complexity is proportional to the product of the bandwidth – delay spread product: $B \cdot T_m$, thus

the number of taps required to achieve ISI free communication is given by $\xi = B \cdot T_m$.
This means that such equalizer of ξ taps have to complete ξ number of multiply-accumulate operations per symbol (MACs). The processing costs grow as the square of the data, and the total complexity is of the order of:

$$O(B^2 T_m).$$

Now focusing on an OFDM-based system susch as WiMAX, one of the most demanding tasks to execute in terms of processing is the fast Fourier transform algorithm, which encloses computing costs of the order:

$$O(N \log_2 N)$$

thus considering that B/N_{FFT} is number of symbols per second, $1/T_m$ is complexity order per symbol.
WiMAX will present nearly linear behavior of computing complexity even under the demanding tasks of forward error correction blocks chosen and the highest data rates:

$$O(B \log_2 B \cdot T_m).$$

Taken into account a channel model, as in [13], [14] where the delay spread is $T_m = 0.202$, the order of complexity of transmission of the whole orthogonal frequency division multiple access (OFDMA) system will have a linear tendency for different bandwidths, as it shown in Fig. 3.

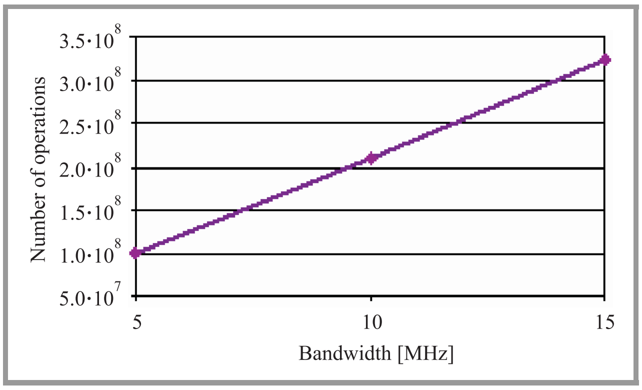

Fig. 3. Order of computational complexity for different transmission bandwidths.

This fact is also true when some FEC as turbo decoder, block turbo codes are used at the receiver side, there are of course variations concerning the system performance, and the computing costs are raised, but the behavior still linear.

4.4. Simulated Processing Complexity

Execution times of the processing blocks on the whole chain were obtained for the different modulation schemes and the code rates selected at every time slot considering downlink transmission and reception. The computational costs in terms of central processing unit (CPU) time rise depending on the number of bits corresponding to modulation scheme as consequence of the number of bits processed to maintain the throughput. The results are shown in Table 3.

Table 3
CPU requirements for different modulation-codes (MCs)

Scheme	CPU time [μs]	
	transmission	reception
1	527.97	1226.29
2	849.41	2349.33
3	1130.79	3792.67
4	1214.68	3999.96
5	1225.93	4038.19
6	1765.09	6594.06

The characteristics of the processor used for the simulations are revealed in Table 4.

Table 4
CPU specifications

Characteristics of the processor	
Processor class	AMDS Athlon 64 X2
Processor speed	3.2 GHz
Processor cores	2
Bus speed	1000 MHz
Performance/speed	19376 MOPS @ 3.2 GHz
Speed efficiency	6.05 MOPS/MHz
Perfomrance/power	19376 MOPS @ 125 W
Power efficiency	155 MOPS/W
Bytes/cycle	15.7
Average latency	17 ns

4.5. Scenarios for Case Study Simulation

The following scenario is defined:

- Downlink transmission.
- Analysis for bit error rate services demand (BER target) of 10^{-4}.
- Path delays, and power of channel taps have been selected according to SUI channel 2 [14].
- The bit error rate performance of the OFDMA system is depicted in Fig. 4. Is important to notice that on the transmitter side, turbo codes are selected together with Reed-Solomon decoder to achieve the quality of service demands. This turbo decoder has a block length of 1024, and it use a stopping criteria. It halts to iterate when the BER target is reached.

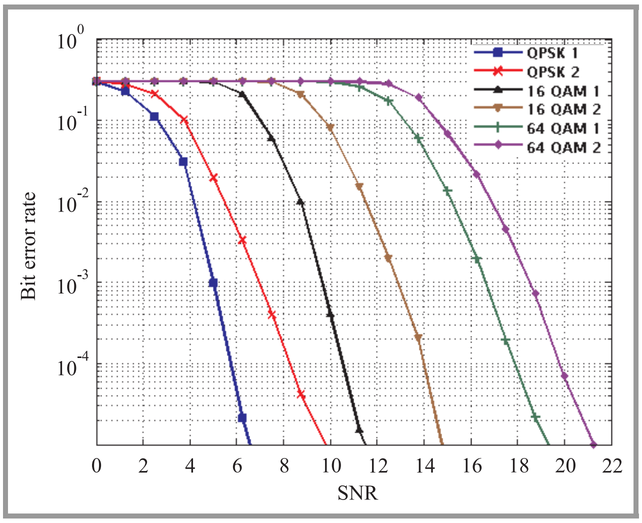

Fig. 4. BER performance of OFDMA system.

Therefore appear two cases that traditional approaches can deploy in time:

- The base station (BS) will choose to optimize its spectral efficiency. The normalized spectral efficiency for the different transmission modes is enclosed in Table 5. The BS will choose for transmission the most efficient modulation-coding scheme for all the users that shall be within its range, in this case 64 QAM 3/4. From the terminal perspective this will be the worst case because of the demanding processing requirements.

- The second strategy is to go towards the other extreme condition: the BS decides that the most suitable transmission mode is the one with the optimal consumption of computing resources. So it selects quadrature phase shift keying (QPSK) as transmission mode for all users to whose is giving service. The minimum spectral efficiency at the base station results in an optimal use of processing resources. There is a difference of 4.5 times between the maximum of computing costs in the strategy 1 (172576.30 MOPS) to the strategy 2 (38351.30 MOPS).

Table 5
Spectral efficiency for different modulation-code schemes

Modulation	QPSK		16 QAM		64 QAM	
Code rate	1/2	3/4	1/1	3/4	2/3	3/4
Spectral efficiency [%]	6.25	9.38	12.5	18.75	25	28.13

In Fig. 5 are illustrated the computational complexity for bandwidths 5 MHz and 10 MHz.
If the hardware platform constraints for the user terminals are known in terms of the maximum processing operations that the CPU can accomplish at the time when the application has to be executed, then some cost function can be defined to achieve the desired goal for a more balanced strategy of decision. Let suppose that the turbo decoder now won't have any halt condition based on the instantaneous BER, but it stops when some maximum number

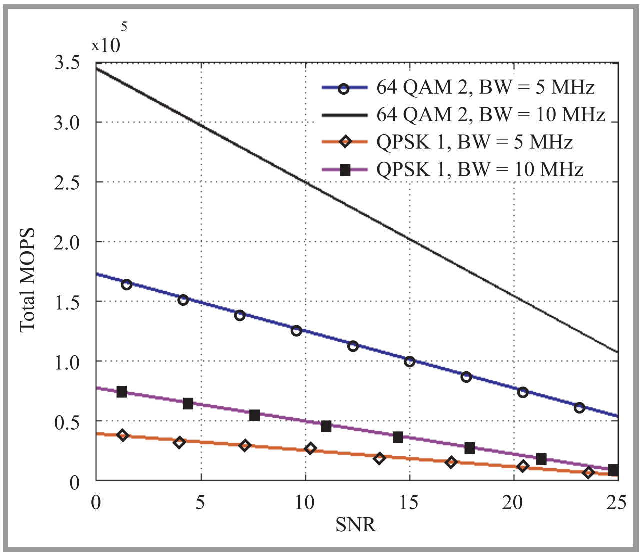

Fig. 5. Computational complexity for the two strategies.

of iterations (NOI) is reached. We take into account two cases: NOI = 20 and NOI = 5 (Table 6).

Table 6
Consumed MOPS for a transmission bandwidth
$B = 10$ MHz

Max NOI	QPSK 1/2	64 QAM 3/4
5	19837.9	89223.07
20	345165.472	76713.988

Is important to notice that a terminal will force to achieve the required quality of service constraint (BER target) at the expenses of these costs, but is clear that some terminals can reach this goal taking into account a better spectral efficiency or an improvement in terms of computational complexity and energy consumption.

4.6. WiMAX Waveform Adaptive Function

The next step is to introduce a version of a real adaptive function which guarantees a desired QoS for some channel realization. The idea is to maintain a sustainable BER target according to the channel conditions defined by an SNR level. It will tend to choose suitable code/modulation mapping scheme taking into account the availability of computing resources for the user and spectral efficiency for the base station. It will obtain the best conditions for the requested QoS, and thus can either transmit with a minimum of computing costs, or negotiate for a lower QoS when channel conditions or the computing costs do not allow that transmission mode. This process is shown in Fig. 6.

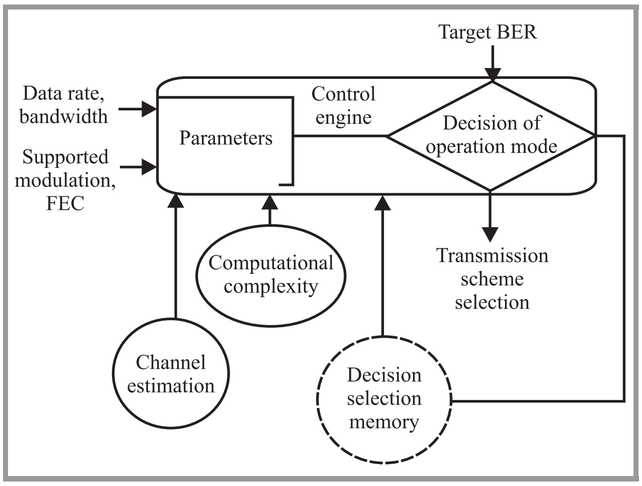

Fig. 6. Algorithm for WiMAX wave-form design.

In order to accomplish this task, we define the following cost function:

$$Cost = 0.7S_{eff} + 0.3C_{eff},$$

where S_{eff} is spectral efficiency, C_{eff} is computational efficiency.

5. Results

On our final analysis we suppose that all user terminals in the whole system are equidistant to the base station. Their computing capabilities are defined so its receiver can deploy either 5 or 20 iterations. The bandwidth of transmission can be chosen between 5 and 10 MHz. Several combinations of parameters can be achieved depending on the resources availability for each user device.

The algorithm use the cost function defined in last section, to set the number of user terminals to whose will assign one (constellation code throughput) triplet and thus certain bandwidth, and certain data rate. The different modulation code schemes are assigned to the two types of terminals that execute 5 or 20 iterations in the FEC in order to achieve

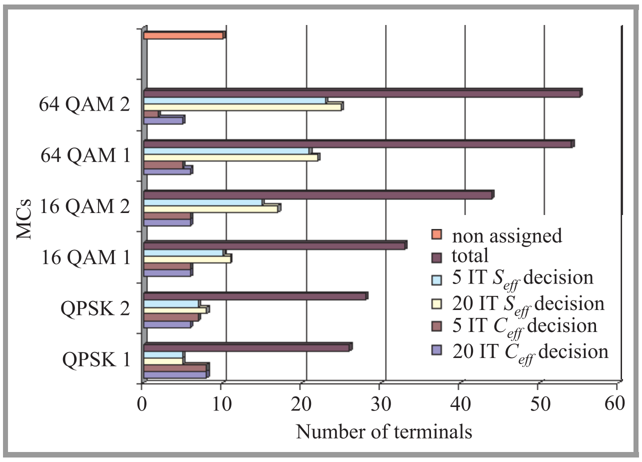

Fig. 7. Modulation-coding schemes assigned to the terminals (BER 10^{-4}) – scenario 1.

the quality of service constraint that was defined. Therefore a suitable allocation is deployed within the system. Results are depicted in Fig. 7.

In order to validate this results, we define a second cost function which to the contrary set more specific weight on the computing resources than to the spectral efficiency:

$$Cost = 0.3S_{eff} + 0.7C_{eff}.$$

The results appear in Fig. 8.

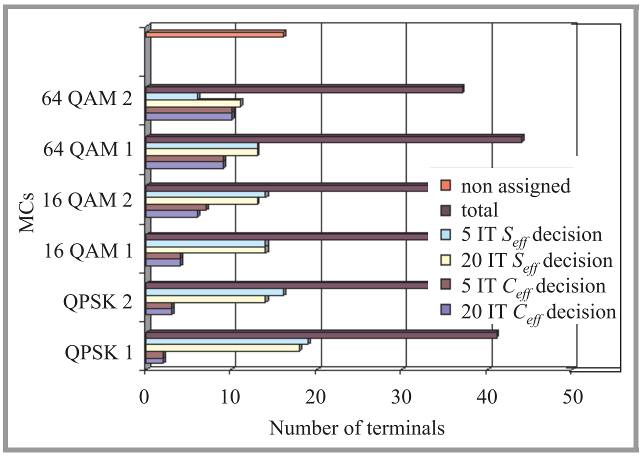

Fig. 8. Modulation-coding schemes assigned to the terminals (BER 10^{-4}) – scenario 2.

Comparing both figures is clear that for some users there will be no transmission settings, because either from the spectral or the computing resources point of view, there are not enough resources available for its service. Then the weight of the cost function defines the tendency of resources and thus the number of terminals to which is assigned each of modulation-coding schemes (Table 7). Better spectral-efficient MC's are assigned mostly for the terminals in Fig. 7, while in Fig. 8, is the contrary case.

Table 7
Terminals scenario

Number of terminals	B [MHz]	Max NOI permited
250	5	20
	10	5

6. Conclusions

In this paper has been illustrated that in order to achieve the necessary level of reliability, granularity and flexibility defined for future radio terminals, it is of major importance to include terminal capacity in terms of its processing power and power consumption. It also has been exposed how is possible to asses' tradeoffs between QoS parameters and computing costs dynamically. Thus, it can be consider that the engine can be updated with tracked information every time slot (in ms).

Several research challenges remain to be overcome before a truly practical system might be deployed. In spite of the technical challenge, it is clear that flexible radios offer hope to meet the resources demands in terms of spectrum, robustness and computing and of new wireless communications.
It is clear that optimization can not be done in devices (only event detection). Engines seeking the optimum set of resources available, must take into account the computing capabilities having its major effect in case when the services are latency limited and a dynamical seamless switch between RAT's (for example UMTS/WiMAX) is conceived.

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References

[1] R. Ferrús, A. Gelonch, O. Sallent, J. Pérez-Romero, N. Nafisi, and M. Dohler, "A feasible approach for E2E QoS management in coordinated heterogeneous radio access networks", in *Proc. IEEE Int. Perf. Comp. Commun. Conf.*, Phoenix, USA, 2005.

[2] J. Mitola, "The software radio architecture", *IEEE Commun. Mag.*, vol. 33, no. 5, pp. 26–28, 1995.

[3] F. K. Jondral, "Software-defined radio – basics and evolution to cognitive radio", *EURASIP J. Wirel. Commun. Netw.*, no. 3, pp. 275–283, 2005.

[4] V. Marojevic, J. Salazar, I. Gomez, and A. Gelonch, "Computing system modeling for flexible radios", in *Proc. Karlsruhe Worksh. Softw. Radio WSR08*, Karlsruhe, Germany, 2008.

[5] J. Mitola and G. Maguire, "Cognitive radio, making software radios more personal", *IEEE Pers. Commun. Mag.*, vol. 6, no. 4, pp. 13–18, 1999.

[6] J. Andrews, A. Gosh, and R. Muhamed, *Fundamentals of WiMAX: Understanding Broadband Wireless Networking.* Englewood Clifs: Prentice Hall, 2007.

[7] "IEEE Standard for Local and Metropolitan Area Networks" – Part 8: "PHY", IEEE Standard 802.16-2004, http://ieee802.org/16

[8] "IEEE Standard for Local and Metropolitan Area Networks. Admendment 2 and Corregendum 1 to IEEE Std 802.16-2004", IEEE Standard 802.16e-2005, http://ieee802.org/16

[9] J. Escoda *et al.*, "QoS and computational cost in wireless WiMAX". Escola Superior de Castelldefels, Universitat Politècnica de Catalunya, Spain, June 2008.

[10] A. J. Goldsmith and S.-G. Chua, "Variable-rate variablepower MQAM for fading channels", *IEEE Trans. Commun.*, vol. 45, no. 10, pp. 1218–1230, 1997.

[11] T. Keller and L. Hanzo, "Adaptive modulation techniques for duplex OFDM transmission", *IEEE Trans. Veh. Technol.*, vol. 49, no. 5, pp. 1893–1906, 2000.

[12] WiMAX Forum, "Mobile WiMAX" – Part I: "A Technical Overview and Performance Evaluation", 2005, http://www.wimaxforum.org/home/

[13] M. Komara, "SDR architecture ideally suited for evolving 802.16 WiMAX standards", Airnet Communications Corporation Press, Melbourne, USA, 2006.

[14] D. S. Baum, "Simulation the SUI channel models", IEEE 802.16 Broadband Wireless Access Working Group, 2004.

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