Run-Time Control For Software Defined Radio

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***Abstract*— A control system is presented, which adapts at run-time a software defined radio to the dynamic external environment. The goal is to operate with minimized use of resources and energy consumption, while satisfying an adequate quality of service. The control system is based on a model, which selects the most optimal configuration based on off-line gathered information and on-line measurements.**

I. Introduction

In this paper, a control system is presented, which adapts at run-time a software defined radio (SDR) to the dynamic external environment in order to operate in an efficient manner.

The next generation of mobiles and base stations needs flexible architectures, such as Field Programmable Gate Arrays (FPGAs), Digital Signal Processors (DSPs) and general-purpose processors, e.g. MIPS and ARM processors. The major motivations to move from application specific integrated circuits (ASICs) to such flexible architecture are:

- the difficulty (effort, costs) to implement the new complex standards on ASICs
- the ease of following emerging standards
- the reduction of the time to market, especially for minor updates
- the ease of bug fixing

For a static ASIC implementation, the parameter settings are optimized at design time for a worst-case situation, which leads to an overkill for good (typical) circumstances. The application of flexible architectures offers the possibility to tune the settings of a SDR at run-time to the current wireless environment, even in continuously changing conditions. In this manner, the effort to achieve the requested quality can be reduced. In other words, overkill is avoided, which can be translated in a reduction in energy consumption for a mobile, or savings in the necessary computing resources for a base station.

To support this run-time adaptive behaviour, trade-offs between different parameter sets should be made to determine the most optimal set for the current situation. In this paper, we will introduce a control system, which is based on a model that selects at run-time a set of parameters that minimizes the effort, while satisfying the requested quality.

In our approach, we reduce the set of parameters to two performance indicators: the quality and the required effort. Fig. 1 depicts the relationship between the quality and the required effort. The dots represent these two performance indicators for different parameter sets in a fixed situation.

Due to the dynamic external environment of a SDR, the wireless link conditions may change and therefore the quality of the output of the SDR will change for a specific set of parameters. In Fig. 1, this implies that the dots will move in horizontal direction as a function of the time. If the conditions of the external environment become worse, then a dot will move to the right and if the conditions become better, the dots will move to the left.

Considering a specific application, certain quality constraints will apply. We will transform these constraints in a strict quality limit. A quality worse than this quality limit is not acceptable. Furthermore, a certain area left from the quality limit will be considered as a risky zone in the sense that the system is not allowed to stay too long in this area. This is depicted in Fig. 1.

Therefore, when an optimal setting is determined, the optimization goal for the quality is left of the risky zone to maintain a certain 'quality margin', because otherwise

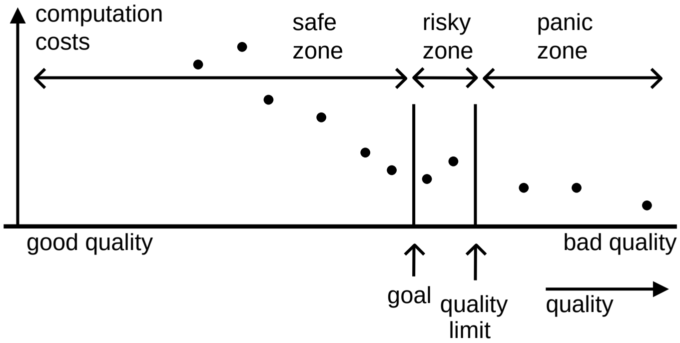

Fig. 1. Quality/costs Relationship For Different Parameter Settings

a quality violation may occur, when the external environment changes only slightly. The optimal set of parameters in Fig. 1 is the first dot on the left side of the goal line: it has the lowest costs (e.g. energy consumption) that satisfies the required quality of service. The quality limit is mainly dictated by the application and cannot be changed. For a specific application, the 'goal' line is at a fixed distance from the quality limit.

Currently, the design of most SDR ensures that worst-case situations are handled well, which provides overkill in 'normal' situations. So, these SDRs operate almost always in safe zone that is mentioned in Fig. 1. The added value of our approach is that we provide a run-time optimization to minimize the operation costs in the safe zone.

II. Related work

Extensive research has been done on parameters for receivers and the optimization of them. However, there are several differences with respect to our research.

Firstly, in most existing literature, the optimization goal is performance optimization, see e.g. [9]. Although we agree that quality is important, our primary point of view is to minimize the amount of effort.

Secondly, in most existing literature, the work is limited to just performance studies of specific parameters or receiver algorithms, to make the best trade-off at design time [6]. Adaptation of the parameters to the current dynamic environment is not considered. Instead, we investigate the *run-time* adaptation of parameters using quality of service concepts at the radio level.

Thirdly, the scope of most existing research is limited to the investigation of only a part of the WCDMA system to model the effect of an isolated parameter. E.g. the effect of spreading is investigated under specific conditions [1], [3]. In our research, we develop a general framework which can be used for the complete SDR in real-world circumstances.

To the best knowledge of the authors, our *general approach* for *minimizing the effort at run-time* using *quality of service at SDR level* is unique.

III. Approach

The heart of the control system is a model that makes trade-offs between different sets of parameters and decides which set should be used. The model has to be as simple as possible, because the time to make a decision is limited and the computational costs have to be low (the cost of selecting an optimal set of parameters should not nullify the achieved energy savings with regard to a fixed set of parameters that is used for worst-case circumstances).

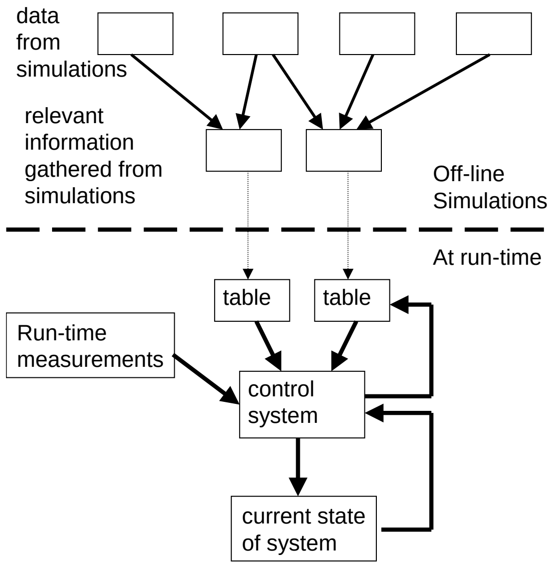

Fig. 2. Information Used By The Control System

Hence, computational intensive optimization methods, like generic algorithms or simulated annealing are not usable.

In our approach, different information sources are used (as depicted in Fig. 2) to achieve a simple model which controls the decisions. First, a lot of scenarios (a combination of a particular external environment and parameter set) are simulated to gather data. In the next section, we describe this process for a RAKE receiver. These data are processed with the goal to investigate the relationship between parameters, recognize patterns, and to simplify the complex system to something that can be controlled with a limited number of parameters. The interpretations of the simulations are summarized in a few tables that are used by the model. In the real system, the tables can be updated with more accurate data at run-time.

Second, the model uses on-line measurements to predict the quality of the current situation (i.e. the position of the dot representing the current parameter set in Fig. 1). The on-line measurements give an indication of the current environment, so that the terminal can adapt well to this environment. The measurements also give a feedback on the effect of changing parameter sets.

Third, the current status of the SDR is involved in the decision process.

IV. Application

Our control system will be demonstrated with a wide code division multiple access (WCDMA) RAKE receiver [5], [4], [8], in combination with a turbo decoder [2], as shown in Fig. 3. This combination can be used in an UMTS terminal or base station.

In [7], the behaviour of the RAKE receiver/turbo decoder combination is studied by means of simulations.

Goal of this study was to identify the most important parameters with regards to quality and energy costs, to analyse the relations between the parameters, and to find a way to predict the quality on the base of measurements, instead of external environment parameters. The most important results which will be used by our control system, will be reported here. For an in-depth discussion about the simulations, see [7].

The quality is expressed in bit error rate (BER) and the costs are expressed in number of operations needed for the datapath (excluding control costs).

A. Turbo Decoder Performance

In a first simulation the relation between the input of the turbo decoder (=output of the RAKE receiver) and the output of the turbo decoder has been investigated. The objective was to find the maximum amount of errors that the turbo decoder is able to correct in a frame. In Fig. 4, the BER from the RAKE output versus the BER from the turbo decoder output after 10 iterations, under poor channel conditions is given.

With this plot, a prediction can be made about the prospect that the turbo decoder can correct the frame as a function of the number of errors in the frame that comes from the RAKE receiver. As can be seen from the plot, this prediction can be made very accurately. If the BER of the RAKE output is more than 0.2, turbo decoding can not recover all the errors in the frame. Applying turbo decoding on such frames is useless and a waste of energy. If the BER at the RAKE output is smaller than 0.18, the turbo decoder is almost always able to recover all the errors in the frame. The BER range of the RAKE output in which there is a high uncertainty about what the result will be after the turbo decoder is small.

B. Gain for RAKE parameters

The most significant parameters for a RAKE receiver are the number of fingers and the spreadingsfactor. Therefore, these two parameters will be optimized by the control system.

Increasing the spreadingsfactor will improve the quality of the output of the RAKE receiver. If the amount of improvement - the gain - can be predicted accurately, this can be used in the control. The simulations in [7] show that the gain for changing the speadingsfactor can be predicted very well, if the number of fingers and the current RAKE output BER is known.

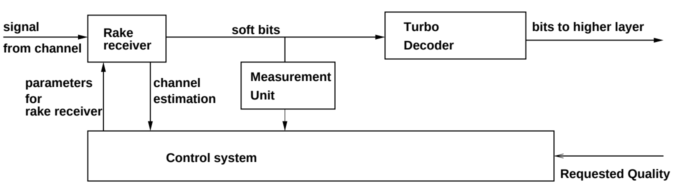

Fig. 3. The Control System Of The Terminal

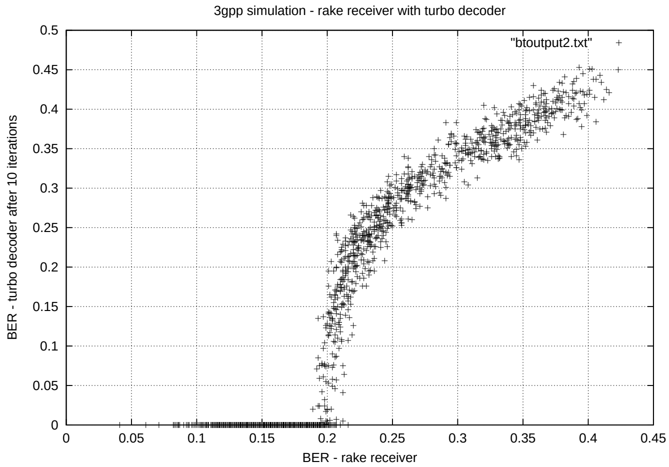

Fig. 4. Limits Of Turbo Decoding

This means that independent of external parameters, a reasonable good prediction can be made about the gain that can be reached if the spreadingsfactor is increased.

Similarly for the number of fingers, the gain is predictable if the power of the different paths is equal. However, if the power of the paths is not equal, the gain will be less. Therefore, the gain figures for the situation with paths with equal power can only be used as an upper bound on the gain that is possible.

V. Control System

In the control system three main states are used, that are equivalent with the three zones in Fig. 1. These states and possible state transitions are depicted in Fig. 5 and described in the first paragraph. In the second paragraph, an optimization process within the safe state is described.

A. Main states

safe - In a safe situation, the current set of parameters leads to a quality better than the minimum quality that is requested by the application. The safe state has two sub states, described in the next subsection.

panic - In a panic situation, the quality is worse than the minimum quality that is requested by the application. The control system tries to improve the quality immediately by adding fingers and/or enlarging the spreadingsfactor. If no better situation is possible, the requested quality can not be delivered.

risky - In a risky situation, the quality is close to the minimum quality that is requested by the application and a more efficient implementation with another set of parameters is impossible. If this risky situation exists for a longer time, the control system will change to a new set of parameters that brings the system back to a safe state. An immediate adaptation is avoided, to prevent adaptation for a short disturbance in the environment. The decision to adapt the system depends on the history, and the difference between the measured quality and the minimum required quality. The smaller the difference, the faster the model will react to adapt the system. This is depicted in Fig. 6. A simple linear function, see Equation 1, gets the BER measurement of a block from the RAKE receiver as input, and gives a damping factor as output. The damping factors for the last n blocks are summed together, see Equation 2. If the total sum is larger as one, the model will adapt the system to enter the safe state again. The number n should be small (e.g. five), because the external environment can change fast.

$$damp(BER_{cur}) = \frac{1}{n} + ((BER_{cur} - BER_{goal}) * (\frac{1-\frac{1}{n}}{BER_{limit} - BER_{goal}})) \quad (1)$$

$$d = \sum_{i=0}^{n-1} damp(BER_{current\_block\_number-i}) \quad (2)$$

B. Optimization

In the safe state, the model tries to optimize the operation costs. For each parameter, the following procedure is executed. First a new BER is predicted for a change of the specific parameter. The prediction is made by multiplication of the current BER by the gain factor from the off-line computed accompanying gain table. If a change of the parameter is allowed; i.e. the expected quality after the change is below the goal limit depicted in Fig. 1, the change is effectuated. After the reception of the next block, the effect of the change can be evaluated by the estimated BER of this block. If it is not possible to change the parameter, it is computed at which BER the change could be implemented. We call this computed BER the BER_reconsider. So, for each parameter a BER_reconsider is computed. The maximum BER_reconsider value and the associated parameter is stored. If the external environment becomes better, and the estimated BER of the RAKE receiver output passes this BER_reconsider value, it is possible to effectuate a change for this parameter.

Note that in the safe state at most one parameter with one step is changed. After the change, the estimated BER is evaluated. We use this approach to avoid an accumulation of prediction errors. A problem with this approach is that global optimum, which e.g. may be achieved by simultaneously changing two parameters, may not be discovered. We use this approach for simplicity reasons, because the effort to compute the model should be low.

In a stable situation all parameters are optimized, and the control system only checks the estimated BER against the stored maximum BER_reconsider value. Expensive optimization evaluations are minimized in this way.

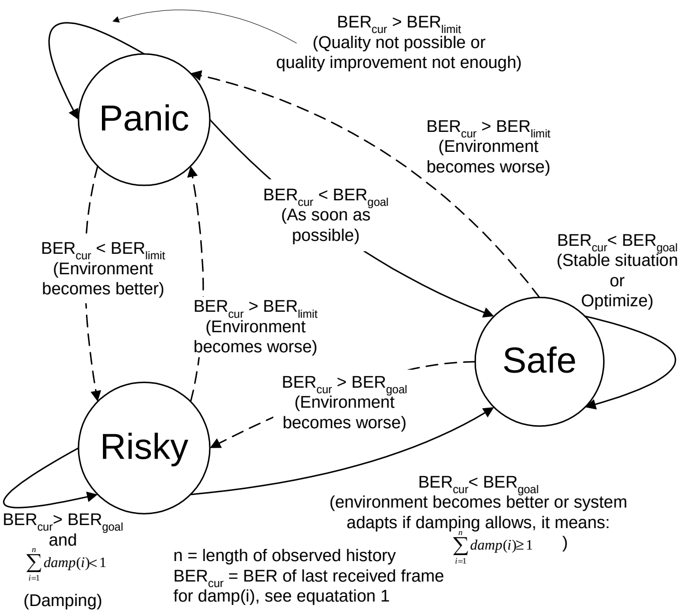

Fig. 5. State Machine Of The Control System

VI. Results

The proposed control system is implemented in our simulation environment [7]. In Fig. 7, simulations are shown of the behaviour of the control system, when the number of users decreases. In this situation, the external environment becomes better. The five graphs in Fig. 7 represent (top - down): (1) the quality of the output of the RAKE receiver expressed in BER, (2) the costs of the RAKE receiver expressed in number of operations, (3) the number of simultaneously transmitting users, (4) the number of fingers of the RAKE receiver and (5) the spreadingsfactor used by the RAKE receiver. On the horizontal axis the sequence number of the transmitted block is shown. Blocks contain 1000 bits. As can be seen from the figure, the number of fingers and the spreadingsfactor are decreased as soon as possible, whereas the quality is maintained below the

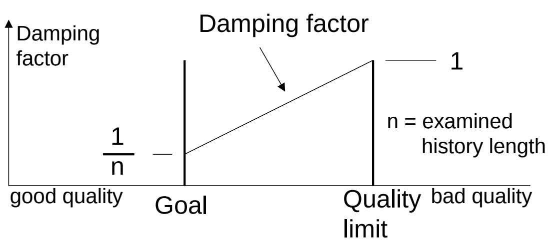

Fig. 6. Damping

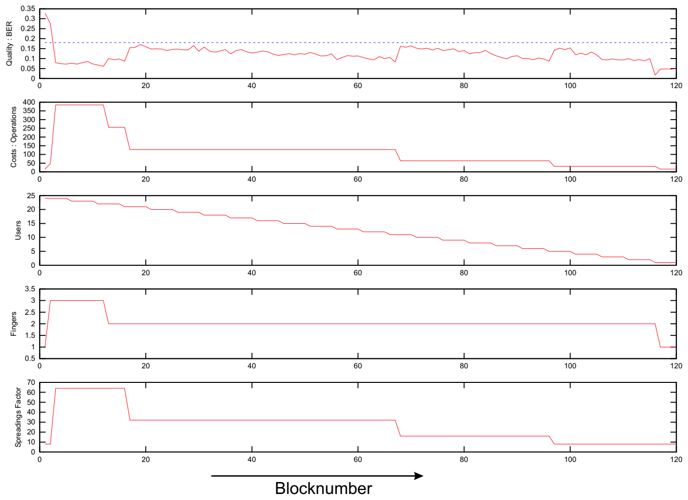

Fig. 7. Decreasing Number Of Users

quality limit of 0.18. Note that the costs for the worst-case situation are much higher than the average costs.

In Fig. 8, a similar figure is shown, but now for an external environment with dramatic changes in the quality is simulated by fast changing the number of users. As can be seen from the figure, the control system adapts very fast to the new situation. After reception of a few blocks, the system is back in a state with an acceptable quality. Within UMTS, a frame contains 38400 chips and is transmitted in 10 ms. So, for a block with 1000 bits that is turbo encoded with rate 1/3 and transmitted with a spreadingsfactor 32, the transmission time of the block is about 25 ms. Therefore, the time to recover from dramatic changes is about tenths of ms.

VII. Conclusions

The presented control system adapts the terminal to the dynamic environment through maintaining a satisfying quality, while minimizing the operation costs. After dramatic changes in the external environment, the control system is able to recover the quality to an acceptable quality range very fast. Therefore, the control system satisfies the expectations.

Compared to a system that is optimized for the worst-case situation, substantial savings can be achieved. In our simulations, savings with a factor of three were no exception.

The control system presented here has been applied to a specific RAKE/turbo case. The data required by the control system are:

- the quality limit (application dependent)
- the width of the risky zone (application dependent)
- per parameter the:
  - the range
  - the step-size
  - a gain table

These data can be gathered for other applications as well. Therefore, we believe that the control system can be used as a general framework, also for other applications. For example, the turbo decoder can very easy be replaced by another kind of forward error decoder.

The presented control system has attractive properties:

- it is able to handle a unpredictable time-variant changing environment with a lot of parameters
- it is simple and therefore:
  - possible to compute at run-time.
  - suitable to use in a mobile terminal with scarce energy resources.
- it is fast enough (within tenths of ms) to react to a fast changing environment.
- it is able to handle parameters with discrete ranges.

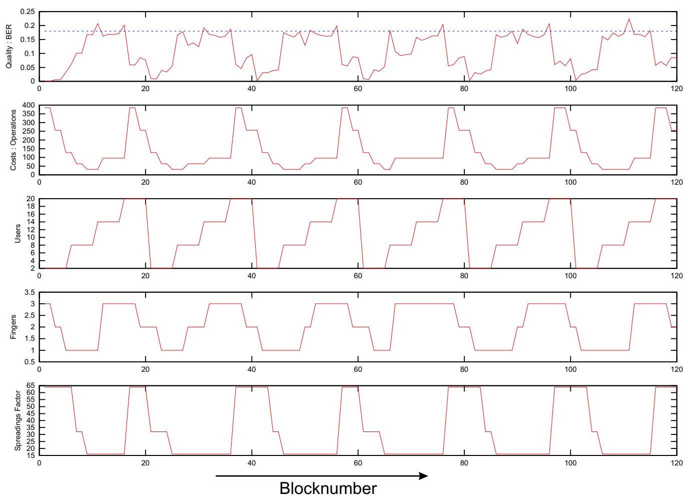

Fig. 8. Dramatic Changes In The External Environment

VIII. Future work

Using a lower spreadingsfactor will result in a higher bandwidth. In this case the receiver (including the analog part that is responsible for a considerable part of the energy consumption of the receiver) can be switched off sooner, saving energy. Therefore, the use of dynamic power management should be included in the trade-offs that are made.

The optimization strategy could be improved. Through the current step by step approach of changing at most one parameter at a time, global optimization is not possible.

The cost of the effectuation of decisions should be included in the model. For example, a change of the spreadingsfactor requires negotiations between the base station and the mobile.

Additional quality constraints like a minimal throughput should also be taken into account.

More investigations in parameters like the blocksize and the puncturing rate are required to achieve a more complete model.

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