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Environment-Adaptable Efficient Optimization for Programming of Reconfigurable Radio Frequency (RF) Receivers

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***Abstract*—Software defined radio has been developed for supporting multi-standard radio receivers, but remains vulnerable to interference. In order to overcome this interference challenge, this paper proposes replacing the fixed wide-band Radio Frequency (RF) front-end in software radio receivers with a reconfigurable RF front-end. We show that a software radio with an optimally chosen reconfigurable RF front-end outperforms fixed RF software radios, when the latter suffers from inter-modulation of blockers caused by non-linearity of its RF front-end. Moreover, we propose a fast optimization algorithm for selecting an optimal configuration of the reconfigurable RF front-end in radio environments with interference. This algorithm selects from among the available configurations of the RF front-end, and improves SINR by adapting to the blockers present, while requiring only a small number of trials to select the appropriate configuration. Thus, a reconfigurable RF front-end, when used in conjunction with a software radio, can effectively realize the development of multi-standard wireless communication systems.**

I. Introduction

Multi-standard radio receivers are important for future wireless communication systems because of the plethora of communication standards that must be handled by modern radio receivers. To develop a multi-standard receiver, Software-Defined Radio (SDR) has been proposed, initially with a fixed wide-band Radio Frequency (RF) front-end, so as to allow operation over a wide range of frequencies. Recent studies have proposed SDR with a selection of narrowband RF front-ends. In these, an external RF front-end with several (separate) RF paths are introduced for each intended communication standard, but share the same Intermediate Frequency (IF) or baseband path after signals are down-converted by a mixer [1]. Also, tunable RF filters have been introduced into the wide-band RF front-end of homodyne architectures [2], and tunable antennas have also been proposed to improve the performance of the multi-standard radio platform [3].

The U.S. Defense Advanced Research Projects Agency (DARPA) has recently proposed the novel concept of a reconfigurable RF front-end, in which various types of RF components (conceivably arranged in component banks), may be used to select different architectures, including heterodyne and homodyne, dynamically [4]. The reconfigurable RF front-end can change its operating channel flexibly based on the requirements of the communication standard it is implementing. Further, amplifiers, filters, and mixers in each stage can be reconfigured according to the chosen architecture and standard. This increases reusability of the RF components, and allows novel architectures in the RF front-end, so that it is a promising alternative to the fixed or narrowband front-ends used in SDRs presently.

With a reconfigurable RF front-end, an important challenge is to find an optimal configuration for a particular communication standard. Recently, [5] investigated reconfigurable RF front-ends for radio receivers, and proposed a method to find the optimal configuration, to minimize receiver power while yielding adequate Signal to Noise Ratio (SNR), in an ideal environment with no interference. In that method, a greedy algorithm is applied to select the RF components from among those available in the RF front-end, while enforcing the minimum SNR criterion. While those results provide a starting point for our paper, they do not specify how to adapt the RF front-end to a *changing RF environment* - specifically to the appearance of large interferers and blockers. In the presence of interference, the optimal configuration is one which has the lowest power consumption and adequate quality of communication as measured by the *Signal to Interference and Noise Ratio* (SINR).

The main difficulty in finding the optimal configuration is the adaptation complexity, measured in the time needed to discover the correct reconfiguration, due to the exponential increase in the number of possible configurations when the number of RF components (amplifiers, filters, and mixers) is large, and when there are several stages of RF signal processing. When the reconfigurable radio is initially programmed, several base configurations (i.e., default configurations) can be pre-programmed into it, based on the desired communication standards. However, the spectral environment is dynamic, with blockers and large interferers appearing randomly at different frequencies. This cannot be pre-programmed exhaustively, since there are too many possible scenarios to be considered. Rather, a fast algorithm can quickly discard infeasible choices and select from a few promising candidate configurations in order to adapt to interferers in real-time.

In this paper, we present an environment-adaptable fast

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optimization method, which can obtain the optimal configuration in the presence of interferers. Thus, the method can be used in real-time to adapt the reconfigurable RF front-end in an SDR. The remainder of this paper is organized as follows. In Section II, we introduce the architecture of a reconfigurable RF front-end for SDR. In Section III, we present our fast optimization algorithm, elaborating on three stages that are required: Profiling step in *Factory mode,* and Exploring step and Searching step in *Theater mode*. We show numerical results in Section IV, and conclude the paper in Section V.

II. RECONFIGURABLE RF FRONT-ENDS

Traditionally, multiple fixed narrow-band RF front-ends have been used for communication systems, where each front-end is designed for a single communication standard. In order to meet the emerging needs of multi-standard platforms, which typically use an SDR, new types of RF front-ends are required. Traditionally, a fixed wide-band RF front-end is used in SDR, so as to cover multiple bands of interest, as shown by Figure 1(a). (This figure is based on a popular USRP SDR [6]).) Flexibility in such a front-end is obtained by changing the operating frequency of the local oscillator used for mixing from tens of MHz to a few GHz. In order to support operation over this large range of frequencies, this front-end uses wide-band amplifiers and mixers in a homodyne architecture, depending on which RF daughter-board is chosen for the SDR. However, this front-end precludes the use of RF filters [3], so that the signal of interest becomes vulnerable to inter-modulated signals. This phenomenon occurs when two or more large interferers lying outside the channel of the signal of interest, produce *in-channel interference*, due to non-linearity of the components in the wide-band RF front-end. In a typical radio receiver, especially in the military space, there may be several large interferers - not just in the band of interest, but due to the wide-band nature of the front-end, even far from the band of interest - which can cause inter-modulation interference to the desired signal.

Unlike the fixed wide-band RF front-end, in a reconfigurable RF front-end of SDR, RF filters can attenuate the power of large interferers, without compromising the receiver sensitivity by attenuating the signal of interest. This can alleviate the inter-modulated interference, thus improving the SINR. Further more, appropriate choices of amplifiers and mixers can also be made to achieve the correct trade-off between sensitivity and selectivity, depending on the dynamic environment. A reconfigurable RF front-end for SDR is shown in Figure 1(b). While a fixed RF front-end is substituted with a reconfigurable RF front-end, an analog-to-digital converter and a digital front-end is retained in SDR.

To demonstrate the usefulness of reconfigurable RF front-ends, we compared it to a fixed wide-band front-end, using the Simulink platform of Mathworks, augmented with the SimRF toolbox. The scenario simulated was as follows. The signal of interest is a IEEE 802.11g WLAN signal with carrier frequency 2.4 GHz and bandwidth of 20 MHz, received at -75 dBm. There are two interferers located at 2.475 GHz and 2.550 GHz. The first interferer is received at -30 dBm while the second interferer is received at powers ranging from -100 dBm to 0 dBm. (This range is selected because blockers of power up to 0 dBm may be observed above 500 MHz, according to the survey in [7].) The fixed wide-band RF front-end has a digital attenuator whose gain can be varied from -0.5 dB to -31.5 dB. The reconfigurable RF front-end has 9747 configurations, one of which is optimal. Each of two narrow-band RF filters is reconfigured by 19 configurations, all with various center frequency, filter order and bandwidth [8]. Each of three amplifiers is reconfigured by three configurations, using different gain, nonlinearity and noise figure. After down-conversion by the mixer, both the systems use an IF filter to remove out-of-band interference, followed by a digital SDR to do digital channel selection and digital down-conversion into baseband. These steps are typical of an SDR such as the USRP. A baseband 802.11g demodulator then decodes the obtained baseband signal.

The maximal possible SINR, obtained by varying the attenuator (fixed RF case) or by choosing the optimal configuration (reconfigurable RF case), is plotted against the second interferer's power in Figure 2. We observe that the SINR of the fixed wide-band RF front-end drops dramatically to reach 0 dB, when the interferer power is higher than -50 dBm. However, the reconfigurable RF front-end has an SNR of 18.8 dB even with very high interferer power up to 0 dBm. Notice that the interferers were located far from the signal channel of interest. These interferers are removed by the IF filter that precedes the SDR in both cases. The degradation in performance in the fixed RF case is mainly due to the non-linearity of the RF front-end, which causes inter-modulation interference to appear in the channel of interest. While the inter-modulation interference is typically weak, it becomes significant when the interferer power is large, as has happened in the fixed front-end case. On the other hand, the reconfigurable front-end allows judicious use of RF filters, so that the interference can be attenuated sufficiently before it can cause significant inter-modulation in the subsequent RF chain. Thus, we conclude that the reconfigurable RF front-end, properly adapted, can outperform the fixed wide-band RF front-end when there are high power interferers, due to non-linearity induced inter-modulation. Therefore, the reconfigurable RF front-end can be used to obtain a reliable multi-standard platform.

The optimal configuration in the reconfigurable RF front-end was obtained using the algorithm specified in [5]. Since that algorithm is greedy, based on the measured performance of sequentially selected configurations, it works well in the presence of interference such as in this case, as well as in its absence (which was its original design scenario). However, the algorithm requires testing a large number of configurations before it finds the optimal one. This may not be a severe limitation in the *Pre-theater mode*, when the radio is being pre-programmed for use in the field. Presumably, a comprehensive set of simulations or real measurements can be made, according to the sequence specified by the algorithm, until the optimal one is found in Pre-theater mode. However, in *Theater mode*, when the radio deployed is being used, a large number of configurations cannot be tested, since the delay in selecting the configuration may be unacceptable, or the environment may change during that time, rendering the selection sub-optimal. Thus, in the next section, we show how to adapt the radio quickly in Theater mode, based on the observed interference environment.

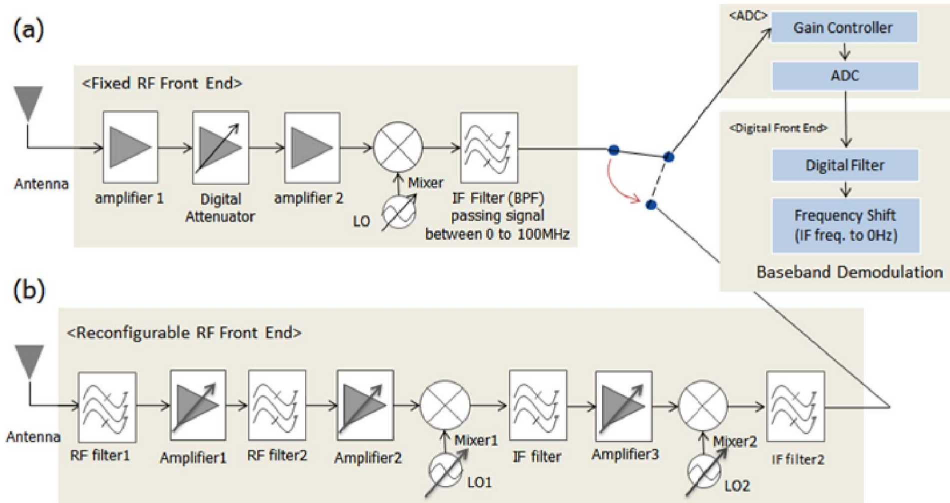

Fig. 1. (a) Fixed wide-band front-end, and (b) reconfigurable RF front-end in SDR.

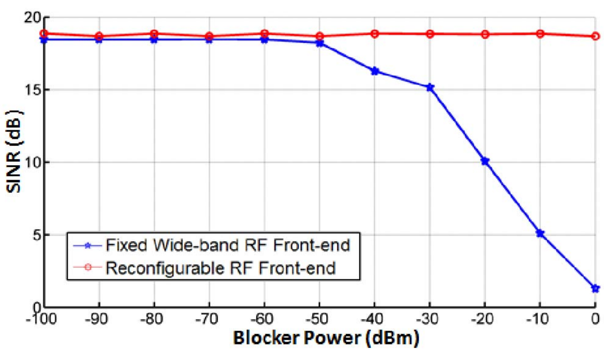

Fig. 2. SINR (dB) vs blocker power (dBm) of fixed wide-band RF front-end (blue) and reconfigurable RF front-end (red).

III. Dynamic Adaptation of Reconfigurable RF Front-end

We propose an environment-adaptable fast optimization method for a reconfigurable RF front-end. The main goal of our proposed algorithm is to efficiently adapt a reconfigurable RF front-end to blocker distribution in the communication environment. Also, the computational cost of the optimization method is critical for adaptation of a reconfigurable RF front-ends, because an optimized configuration should be repeatedly tuned for adapting to the communication environments in real-time.

In order to find an optimal configuration of the reconfigurable RF front-end, the optimization problem can be mathematically formulated as follows,

$$\min_{\mathbf{x}} \quad F(\mathbf{x}), \quad \text{s.t. } S(\mathbf{x},t) = min(g_1(\mathbf{x},t) - G_1, \cdots, g_{N_g}(\mathbf{x},t) - G_{N_g})) \geq 0 \tag{1}$$

where the vector-valued $\mathbf{x}$ is one of the available configurations for a reconfigurable RF front-end and the value of each element of $\mathbf{x}$ is a parameter of an individual component. $F(\mathbf{x})$ is a cost function (such as power consumption of the configuration), which needs to be minimized, and $S(\mathbf{x},t)$ is a constraint function, which combines all constraint functions $g_j(\mathbf{x},t) \geq G_j$ for $j \in \{1, 2, \cdots, N_g\}$ at time t (signal-to-interference-plus-noise ratio, area, cost, etc.). The constraint function $S(\mathbf{x},t)$ varies with the time-varying blocker distribution in real-time. In order to solve this optimization problem efficiently in real-time, we define three stages in Factory mode and Theater mode as below:

(A) *Profiling stage in Factory mode*: When manufacturing a reconfigurable RF front-end in a factory, a **Configuration Profile Table** is built in order to provide information of possible configurations in the reconfigurable RF front-end. For example, we decide if a configuration operates for a signal of interest based on bandwidth and carrier frequency of filters for each configuration in the table. Also, third-order intercept point (IP3), a metric of non-linearity of RF components, needs to be given in the Configuration Profile Table for predicting inter-modulation effect of blockers in our algorithm.

(B) *Exploring stage in Theater mode*: A reconfigurable RF front-end updates real-time information for practical use. In particular, we periodically update a **Real-Time Table** using estimated SINR, based on the Configuration Profile Table created in Factory mode and the blocker distribution given by **Spectrum Detector**. The Spectrum Detector corrects information of the central frequencies and power of blockers and the signal of interest at time $t = t_0$. In order to extract the current signal information, the Spectrum Detector has a homodyne architecture without amplifiers of the fixed front-end Figure 3. It operates by observing received signals in frequency domain while tuning a sinusoidal frequency of the local oscillator in a mixer [9].

(C) *Optimizing stage in Theater mode*: We run an environment-adaptable and fast optimization algorithm to find the optimal configuration $\mathbf{x}_t^{(opt)}$ of a reconfigurable RF front-end at time t. Efficiency of the algorithm is improved by reflecting real-time information of communication environments using the Real-Time Table as well as the Configuration Profile Table. Therefore, in Theater mode, we solve an optimization problem in (1) at time $t = t_0$.

Having defined the optimization problem and three modes of our method, we will now present the details of algorithms in the three defined modes. We first explain non-linear parameters related to inter-modulation of blockers and describe how to estimate the non-linear parameters for the Configuration Profile Table in Subsection A. Then, we will discuss how to relate the inter-modulation effect to profile information given in the Configuration Profile Table and Spectrum Detector in Subsection B. Finally, we will present our environment-adaptable fast optimization algorithm and its pseudo-code in Subsection C.

A. Profiling Stage in Factory Mode

The Configuration Profile Table contains the important parameters related to properties of each configuration. For example, a filter's behavior in a configuration is described in the table by its central frequency, bandwidth, Q factor, etc. In addition to the filter parameters, there are important non-linear parameters, which are strongly relevant to the blocker inter-modulation effect. In order to estimate the non-linear parameters, we need to start by categorizing blockers.

First, set $B^{(k)}$ is defined as a set of all pairs of blockers, which may cause inter-modulated signals by non-linearity of the k-th configuration of a reconfigurable RF front-end.

$$B^{(k)} = \{(b_m, b_n) : |2 \cdot F_m - F_n - F_c| < 0.5 \cdot \mathrm{BW}\}, \qquad (2)$$

where the two pulse blockers b_m and b_n from Spectrum Detector are located at the frequencies of F_m and F_n ($F_m < F_n$), respectively. F_c is the carrier frequency of the signal of interest and BW is the bandwidth of the signal of interest.

Since there are N_k filters in the k-th configuration of the reconfigurable RF front-end, we can align the filters in the order in which the signal passes. Then, the passband of i-th filter is denoted by P_i. A pair of blockers (b_m, b_n) in $B^{(k)}$ may or may not pass the i-th filter (e.g., F_m and F_n may or may not in P_i) for $i \in \{1, 2, \cdots, N_k\}$.

Now, we can group pairs of blockers (b_m, b_n), into N_k subsets ${B_i}^{(k)}$ of set $B^{(k)}$ based on F_m, F_n and passband P_i of the i-th filters as follow,

$$\begin{aligned}{B_i}^{(k)} = \{(b_m, b_n) \in B^{(k)} : F_m \in \bigcap_{r=1}^{i} P_r, F_n \in \bigcap_{r=1}^{i} P_r,\\ (b_m, b_n) \notin {B_{i+1}}^{(k)}\}, \qquad (3)\end{aligned}$$

where $i \in \{0, 1, 2, \cdots, N_k\}$, and ${B_{N_k+1}}^{(k)} = \emptyset$.

There is only one set ${B_i}^{(k)}, i \in \{0, 1, 2, \cdots, N_k\}$ containing any pair of blockers (b_m, b_n) in $B^{(k)}$. If a pair of blockers (b_m, b_n) belongs to ${B_i}^{(k)}$, at least one of the blockers are significantly attenuated by the (i+1)-th filter. Then, after passing through the (i+1)-th filter, inter-modulation of blockers does not occur additively. In other words, the inter-modulation of blockers is caused by non-linearity of RF components, through which blockers have passed before passing the (i+1)-th filter. Suppose parameter IP3$_{i,k}$ represents IP3 of RF components through which blockers have passed before passing through the (i+1)-th filter in the k-th configuration. In this case, IP3$_{i,k}$ for $i \in \{1, 2, \cdots, N_k\}$ would be important to know for predicting inter-modulated signals by blockers, and these parameters need to be included in a Configuration Profile Table.

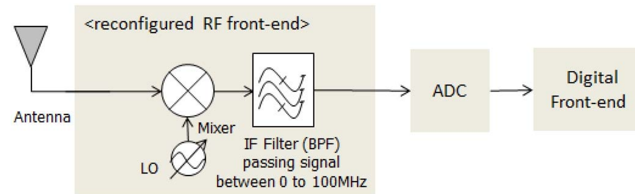

Fig. 3. Spectrum Detector - reconfigurable RF front-end has a configuration that bypasses all filters and amplifiers and has a homodyne architecture.

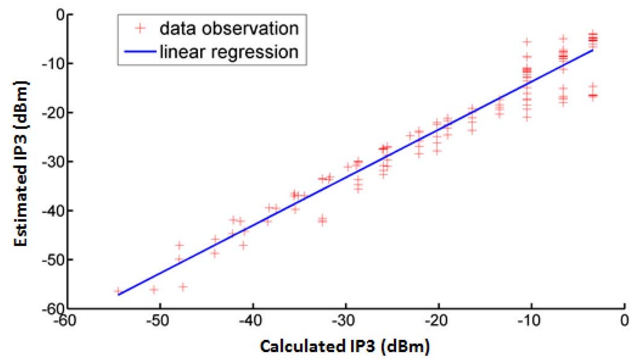

Fig. 4. Estimated of IP3$_{i,k}$ vs. Calculated IP3$_{i,k}$ for $i = 1, 2, 3$ of the reconfigurable RF system in Fig 1 (b).

We will estimate non-linear parameter IP3$_{i,k}$ using two sinusoidal signals belonging to ${B_i}^{(k)}$, satisfying the following condition:

Assume that when two sinusoids of amplitude $A_{1,i,k}$ and $A_{2,i,k}$, respectively, in $B_i^{(k)}$ pass through the reconfigurable RF front-end, the received inter-modulated signal has amplitude $A_{out,i,k}$. Assume that when a sinusoid of amplitude of $B_{in,k}$ at frequency F_s in the band of the signal of interest, passes through the reconfigurable RF front-end, then the received signal at F_s has amplitude $B_{out,k}$.

Then, IP3$_{i,k}$ is given by the following formula,

$$\frac{1}{\mathrm{IP3}_{i,k}} = \frac{A_{out,i,k}}{{A_{1,i,k}}^2 \cdot A_{2,i,k}} \frac{B_{in,k}}{B_{out,k}}. \qquad (4)$$

Thus, varying the frequencies of the generated one or two sinusoids and sending the sinusoids through the reconfigurable RF system, we can obtain IP3$_{i,k}$, where $i \in \{1, 2, \cdots, N_k\}$ of the k-th configuration. The estimation result of IP3$_{i,k}$ is plotted in Figure 4. IP3$_{i,k}$, obtained by our estimation method in (4), is on the y-axis, and IP3$_{i,k}$, calculated from the each IP3 and gain of amplifiers, is on the x-axis. We observe the estimated IP3 proportionally increases with the calculated IP3. The variation between the calculated IP3 and the estimated IP3 is because the calculated IP3 on the x-axis did not account for the insertion loss of filters or the gain and the non-linearity in mixers, while the estimated IP3 did.

Therefore, using this method we estimated the non-linear parameters IP3$_{i,k}$, and stored them in a Configuration Profile Table in Factory mode.

B. Exploring Stage in Theater Mode

SINR should be greater than or equal to the SINR specification required by a given communication standard. This is mapped to one of the constraint functions $g_j(\mathbf{x}, t) \geq G_j$ defined in (1).

SINR of the k-th configuration at time $t = t_0$ is given as,

$$\text{SINR}^{(k)} = \frac{P_s}{{P_n}^{(k)} + {P_b}^{(k)}}. \tag{5}$$

We assume that the signal power P_s is obtained directly from the Spectrum Detector and that noise power ${P_n}^{(k)}$ of the k-th configuration is given in the Configuration Profile Table. The term ${P_b}^{(k)}$ is the power of overall inter-modulation signal caused by blockers at time $t = t_0$. The power $P_b^{(k)}$ is given as follow,

$${P_b}^{(k)} = \sum_{i=1}^{N} \sum_{(b_m, b_n) \in B_i^{(k)}} \frac{1}{{\text{IP3}_{i,k}}^4} \cdot ({P_{m,i}}^{(k)})^2 {P_{n,i}}^{(k)}, \tag{6}$$

where ${P_{m,i}}^{(k)}$ and ${P_{n,i}}^{(k)}$ are the powers of a pair of blockers (b_m, b_n), respectively, in set $B_i^{(k)}$ defined in (3).

${P_b}^{(k)}$ will be calculated based on blocker powers, ${P_{m,i}}^{(k)}$ and ${P_{n,i}}^{(k)}$ obtained from the Spectrum Detector and the non-linear parameters, $\text{IP3}_{i,k}$ in the Configuration Profile Table. Because of the dependency on real-time blocker powers in ${P_b}^{(k)}$, SINR$^{(k)}$ in (5) is a time-varying metric. Thus, we need a new table updated in real-time, a Real-Time Table of the time-varying SINR$^{(k)}$ of the k-th configuration, which delivers numerical information about the effects of blockers given in communication environments.

Based on this Real-Time Table, we can find $\mathbf{x}_t^{(max)}$ which has the highest value of SINR$^{(k)}$ using Algorithm 1.

Algorithm 1 Find the configuration $\mathbf{x}_t^{(max)}$ of the highest SINR$^{(k)}$ in all configurations in Real-Time Table at time $t = t_0$.

$\mathbf{x}_t^{(max)} \leftarrow \mathbf{x}^{(1)}$
$S^{(max)} \leftarrow S^{(1)}$.
for $k = 1, 2, \cdots, K$ **do**
  if $S^{(k)} > S^{(max)}$ **then**
    $\mathbf{x}_t^{(max)} \leftarrow \mathbf{x}^{(k)}$
    $S^{(max)} \leftarrow S^{(k)}$
  end if
end for

We can use this to find one of the possible configurations, which would be higher than SINR specification for communication, even with blocker existence in Theater mode. Meanwhile, this answer $\mathbf{x}_t^{(max)}$ of Algorithm 1 may not be the optimal configuration with respect to other constraint functions or cost functions in (1).

C. Optimizing Stage in Theater Mode

The proposed environment-adaptable fast optimization algorithm can now utilize the information in the Real-Time Table for reflecting blockers in the communication channel. The table will be used in the second algorithm for the following purposes:

• **The choice of initial point of the optimization**:
The initial configuration $\mathbf{x}^{(int)}$ of optimization is important to reduce computational cost. This is because finding a point satisfying constraint functions $S(\mathbf{x}, t) \geq 0$ at $t = t_0$ in (1) is the most time-consuming process in the optimization process when the initial point is chosen randomly. However, we set the configuration $\mathbf{x}^{(max)}$ found in Algorithm 1 as our initial point for the optimization process, and thus were able to eliminate unnecessary iterations.

• **Minimization of search space of overall configurations**:
In this step, by looking up the Real-Time Table, we were able to discern and exclude configurations $\mathbf{x}^{(k)}$ that do not satisfy the constraint function SINR$^{(k)} \geq$ (SINR threshold) in the optimization process. Assume that (SINR threshold) = (SINR specification)$-\varepsilon = G_j - \varepsilon$ given in the constraint function $g_j(\mathbf{x}, t) \geq G_j$ in (1). As unnecessary simulations are skipped based on Real-Time Table, the computational cost can be dropped.

The two techniques are applied to a relaxing search optimization method. The details of the proposed optimization method are given as pseudo-code in Algorithm 2.

Algorithm 2 Find an optimal configuration $\mathbf{x}_t^{(opt)}$ based on Real-Time Table at time $t = t_0$

1: $\mathbf{x}^{(tmp)} \leftarrow \mathbf{x}^{(max)}$
2: run simulation for $\mathbf{x}^{(tmp)} \Rightarrow$ obtain $F(\mathbf{x}^{(tmp)})$
3: $\mathbf{x}^{(old)} \leftarrow \mathbf{x}^{(tmp)}$
4: **for** $m = 1, 2, \cdots, M$ **do**
5:   **for** $n = 1, 2, \cdots, N_m$ **do**
6:     $\mathbf{x}^{(tmp)} \leftarrow \mathbf{x}_m(n)$
7:     % search in Real-Time Table
8:     **for** $k = 1, 2, \cdots, N_k$ **do**
9:       **if** $\mathbf{x}^{(k)} = \mathbf{x}^{(tmp)}$ **then**
10:         break
11:       **end if**
12:     **end for**
13:     **if** SINR$^{(k)} <$ (SINR threshold) **then**
14:       continue
15:     **else**
16:       **if** ($\mathbf{x}^{(tmp)}$ has not simulated previously) **then**
17:         run simulation for $\mathbf{x}^{(tmp)}$
18:         $\Rightarrow$ obtain $F(\mathbf{x}^{(tmp)})$ and $S(\mathbf{x}^{(tmp)})$
19:       **end if**
20:     **end if**
21:     **if** $S(\mathbf{x}^{(tmp)}) \geq 0$ **then**
22:       $E_m(n) = F(\mathbf{x}^{(tmp)})$
23:     **else**
24:       $E_m(n) =$INF
25:     **end if**
26:   **end for**
27:   $\mathbf{x}^{(new)} \leftarrow \mathbf{x} = \underset{\mathbf{x} \in \{\mathbf{x}_m(n) | n=1,2,\cdots,M_m\}}{\arg\min} E_m(n)$
28:   **if** $\mathbf{x}^{(new)} = \mathbf{x}^{(old)}$ **then**
29:     break
30:   **else**
31:     $\mathbf{x}^{(old)} \leftarrow \mathbf{x}^{(new)}$
32:   **end if**
33: **end for**
34: ${\mathbf{x}_t}^{(opt)} \leftarrow \mathbf{x}^{(new)}$

If there are M RF components connected serially in a reconfigurable RF front-end, the variable m in line 4 points the m-th RF component, such as amplifiers, filters, and mixers. For the m-th RF component, there are N_m configurations such as amplifier1, amplifier2, etc. The variable n in line 5 represents the n-th configuration of the given m-th RF component. For the current configuration $\mathbf{x}$, $\mathbf{x}_m(n)$ in line 6 is the configuration whose m-th RF component chooses n-th configuration. Lastly, $\mathbf{x}^{(k)}$ in line 9 is the k-th configuration in Real-Time Table such that $\mathbf{x}^{(k)} = \mathbf{x}_m(n)$. Therefore, using the proposed algorithm, we found the optimal configuration $\mathbf{x}_t^{(opt)}$ of optimization problem in (1) at time $t = t_0$.

IV. Results

In this section, the reconfigurable RF front-end in Figure 1 (b) is used as an example to demonstrate the efficiency of the proposed fast optimization algorithm.

A. Simulation Setup

The goal of our optimization of the reconfigurable RF front-end is to minimize the power consumption for a given SINR specification. This RF receiver is designed for the IEEE 802.11g WLAN standard where the carrier frequency is 2.4 GHz and the channel bandwidth is 20 MHz. While the received signal has power of -85 dBm, two pulse blockers have power of -30 dBm at 2.63 GHz and 2.855 GHz, respectively. In this example, Reconfigurable RF front-end is reconfigured by switching two RF filters and three amplifiers. Two RF filters have five possible configurations, respectively, all of which can pass the signal of interest without losing information. The banks of three amplifiers have four possible configurations each. Thus, there is a total of 1600 different candidate configurations for the reconfigurable front-end. The simulation is implemented in MATLAB Simulink.

B. Programming Results

Computational cost is one of the critical values for the evaluation of different optimization methods. Thus, we observed the number of iterations in optimization at time $t = t_0$ for finding an optimal configuration, which is proportional to computational cost. (Time for updating the Real-time Table is not accounted for because it is negligible enough to ignore, compared to the simulation time for iteration steps in optimization.)

In order to demonstrate the performance of our proposed environment-adaptable fast optimization method, we built five different optimization algorithms:

(1) Exhaustive search: All configurations are simulated one by one, and based on the obtained SINR, the exhaustive search method searches an optimal configuration.
(2) Local Relaxation search: In each iteration, only one RF component in a current configuration can be switched to possible configurations in a bank, while other RF components are fixed. A local optimum among the simulated configurations is updated to the current configuration for the next iteration.
(3) Simulated Annealing search: In each iteration, the random neighbor configurations of a current configuration can be simulated by changing possible configurations in a bank. A local optimum among the simulated neighbor configurations is stochastically updated to the current configuration for the next iteration.
(4) Two-phase relaxation search [5]: First of all, the two-phase relaxation search narrows down the search space of configuration using Pareto optimal front. Using a local relaxation search, this method searches a configuration of maximal SNR in the first phase, which is the initial point for the second phase. Then, it searches a configuration of optimal SNR in the second phase.
(5) Environmental-adaptable Relaxation search (Proposed): This method is explained in Section II and III.

TABLE I. Programming results for the reconfigurable RF front-end with different SINR specification

Algorithm		SNR Specification (dB) 6	8	10
Exhaustive	SNR (dB)	13.59	13.59	13.59
	Power (mW)	1.9	1.9	1.9
	simulation	1600	1600	1600
Relaxation	SNR (dB)	10.08	10.08	11.4
	Power (mW)	1.9	1.9	1.9
	simulation	20	20	22
Annealing	SNR (dB)	13.59	13.59	13.59
	Power (mW)	1.9	1.9	1.9
	simulation	1098	1111	933
Two-phase [5]	SNR (dB)	10.08	10.08	11.37
	Power (mW)	1.9	1.9	2.4
	simulation	24	24	24
Proposed	SNR (dB)	11.49	11.49	11.69
	Power (mW)	1.9	1.9	2.53
	simulation	7	7	7

The simulation results are given in Table I. The five different algorithms are compared for different SINR specifications: 6 dB, 8 dB, 10 dB. The first optimization method, the exhaustive optimization, searches all 1600 configurations to find a global optimal configuration. The method is time-consuming for a large search space of the reconfigurable RF front-end. The second optimization method, the local relaxation search, is more practical compared to exhaustive search due to its speed. The optimization search takes 20 simulation steps for the 6 dB and the 8 dB SINR specifications, and 22 simulation steps for the 10 dB SINR specification. As a trade-off, local relaxation search found only local optimal configurations. The third algorithm, the simulated annealing optimization, takes 1098, 1111 and 933 simulation steps satisfying the SINR specification 6 dB, 8 dB and 10 dB, respectively. The simulated annealing optimization is as good as the exhaustive search in terms of finding the global optimum and better than the exhaustive search regarding speed. However, its speed is still much lower than the local relaxation search. The fourth optimization method, two-phase relaxation search, has a slightly higher SINR and simulation time than the local relaxation search. This is because the two-phase optimization detours the search space by finding a configuration of maximized SINR first and then moving to the second-phase of optimization. For the same reason, SINR of optimal configuration in this method is slightly higher than in the local relaxation search.

The fifth optimization method, our proposed method, is the fastest of the five methods. The proposed method completes the optimization process after seven simulation steps for three different SINR specifications. This is because the method chooses the initial point carefully and narrows down the search space of configurations based on calculated SINR in the Real-Time Table. Also, in this method, the SINR of the optimal configuration is higher than the local relaxation search and the two-phase optimization. Therefore, we can verify that the proposed optimization method significantly improves computational cost compared to the other four optimization methods, and it can still find an optimal configuration with acceptable performance.

V. Conclusion

In this paper, we designed an environment-adaptable and fast optimization method for programming a reconfigurable RF front-end. In the proposed optimization method, real-time blocker information is reflected in SINR calculations in order to speed up the optimization process. Numerical experiments demonstrate that the proposed optimization method outperforms other traditional optimization methods for finding an optimal configuration for reconfigurable RF front-ends. In particular, the proposed method reduces the computational cost significantly and finds an optimal configuration after only seven iterations, instead of searching 1600 configurations exhaustively, in blocker existence condition for varying SINR specifications. The main focus of our research is attaining low computational cost (fast convergence) in optimization for a real-time application. Finding a global optimization is not necessary as long as an optimal configuration exists. Therefore, using this algorithm, reconfigurable RF front-ends can move forward to a reliable multi-standard platform for the needs of future communication systems.

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