3. CR parameters and Multi-Objective Fitness Function

3.1. Introduction

Cognitive radios dynamically configure the wireless communication system, which takes benefit of the existing RF environment. The design of the radio link for a particular network configuration and geographic based on multiple parameters that are non-linearly linked. For example, operating frequency, signal-to-noise ratio, different antenna types, data rate, transmitter power, modulation scheme and interference levels are a few of the parameters that should be considered while designing an radio link. These parameters are related to each other and have non-linear and linear linked relationships and are dependent on multi-path fading, interference levels, and network topology.

Figure 3.1 Directed graph indicating how one objective affects another objective.
Demanding a real-time optimal solution for these parameter values is an extremely complicated and tricky task. The result for each of the objective managing these parameters varies and overlaps among each other and thus one objective (source) affects another objective (target) as shown in Figure 3.1. In CR system designing, a several parameters as inputs must be described. The decisions accuracy made by an AI technique are depends upon the quality and amount of inputs to the system. More inputs to the system formulate the radio more knowledgeable, therefore permitting the decision making process to produce decisions that are more precise. The decision variables are (i) at the physical layer: modulation and transmission power order for each sub-carrier; (ii) at the MAC layer: minimum and maximum contention windows sizes, frame size; (iii) at the network layer: index of the associated access point and variable transmission range [Alexandre de Baynast et al., Pages 778-794]. A goal is to define a set of decision variables concerning the CR physical layer only and other layers are out of scope through out in this thesis. There are two sets of inputs to the system: transmission parameters and environmental parameters are discussed in following section.

3.2. Transmission Parameters

In the CR system, decision variables correspond to the transmission parameters that can be handled by the CR system that takes benefit of the SDR that controls the parameters, which are input to a fitness function along with the objectives, and environmental parameters. The fitness function provides a value that represents optimal parameters for the specified objectives. Fitness functions to be used by CR techniques need a specific list of transmission parameters that should be accessible to
the system. These transmission parameters are equivalent to the parameters that are controlled by SDR mechanism.

Table 3.1 Lists of Transmission Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit Power ((P))</td>
<td>Raw transmission power</td>
</tr>
<tr>
<td>Modulation Type ((Mod))</td>
<td>Type of modulation format</td>
</tr>
<tr>
<td>Modulation order ((M))</td>
<td>Number of symbols for given modulation format</td>
</tr>
<tr>
<td>Bandwidth ((B))</td>
<td>Bandwidth of transmission signal in Hz</td>
</tr>
<tr>
<td>Packet Size ((L))</td>
<td>Transmission packet size in bytes</td>
</tr>
<tr>
<td>Symbol Rate ((R_s))</td>
<td>Number of symbols per second</td>
</tr>
</tbody>
</table>

The parameters selected based on literatures cited as transmission or radio parameters used by CRs [J. F. Hauris, pp. 427–431, T. Christian James Rieser’s Dissertation]. The transmission or radio/antenna parameters include values that affect to radio performance and the complete list of parameters used in this thesis to create a fitness function is shown in Table 3.1.

3.3. Environmental parameters

The environmental parameters are associated to network layout and geographic topology. Environmental measurements update the system of the surrounding environment characteristics. These parameters are information concerning the existing wireless environments that are used as inputs to the CR system. These characteristics may include internal information about the radio in use state, and peripheral information representing the wireless channel environment. The environmental
variables can be divided into two groups. The first environment variables that are directly used by the fitness function as key parameters to the function. For example, the parameter of noise power of the channel which is used in the minimize BER. These parameters directly impact the fitness score of the particular objective function. The second environment parameters are observed by the CR system, and decisions regarding the objective function depend upon their values.

Table 3.2 Lists of Environmental Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit-Error-Rate (BER)</td>
<td>Total bits have errors relative to transmitted bits</td>
</tr>
<tr>
<td>Signal-to-noise ratio (SNR)</td>
<td>Ratio of the signal power to the noise power</td>
</tr>
<tr>
<td>Noise power (N)</td>
<td>Magnitude in dB of the noise power</td>
</tr>
<tr>
<td>Battery Status</td>
<td>Predictable energy left in batteries</td>
</tr>
<tr>
<td>Power Utilization</td>
<td>Power utilization of present configuration.</td>
</tr>
</tbody>
</table>

For example battery status parameter, in this regard the system may be observing this parameter while is reduces below a specific threshold, the system may alter the weighting on the objective functions so as to provide the minimize power consumption. Decision-making in CR engine to formulate a definite output, the existing wireless environment should be modeled internally. This model is formed with environmentally sensed data received by the CR system by a peripheral sensor. Several sensors exist to detect characteristics of the wireless environment. The environmental data also used to form the transmission parameters and the wireless channel, performance objectives. The environmental parameters list used are shown in Table 3.2. All parameters discussed as above will utilized in multi-objective optimization and its concept is explored in next following section.
3.4. Multi-Objective Optimization Concepts

Optimization problems are normally stated in a single-objective way. In other words, the process must optimize a single-objective function complying with a series of constraints that are based on constraints given by the real world. A single-objective optimization problem may be stated as follows [Multi-Objective Optimization in Computer Networks Using Metaheuristics, by Auerbach]:

Optimize [minimize/maximize]
\[ y = f(\bar{x}) \]
(3.1)

subject to
\[ H(\bar{x}) = 0 \]
\[ G(\bar{x}) \leq 0 \]

In this case, the function to be optimized (minimize or maximize) is \( f(\bar{x}) \) where vector \( \bar{x} \) is the set of independent variables. Functions \( H(\bar{x}) \) and \( G(\bar{x}) \) are the constraints of the model.

For this problem we can define three sets of solutions:

i. The universal set which in this case are all possible values of \( \bar{x} \), whether feasible or non-feasible.

ii. The set of feasible solutions which are all the values of \( \bar{x} \) that comply with the \( H(\bar{x}) \) and \( G(\bar{x}) \) constraints. In the real world, these variables would be all possible solutions that can be performed.
ii. The set of optimal solutions which are those values of $\bar{x}$ that, in addition to being feasible, comply with the optimal value (minimum or maximum) of function $f(\bar{x})$ whether in a specific $[a, b]$ interval or in a global $(-\infty, +\infty)$ context. In this case, one says that the set of optimal solutions may consist of a single element or several elements, provided that the following characteristic is met: $f(x) = f(x')$, where $x \neq x'$. In this case there are two optimal values to the problem when vector $\bar{x} = \{x, x'\}$.

But in real life, it is possible that when we want to solve a problem, this may need to optimize more than one objective function. When this happens, this is referred to multi-objective optimization.

In general, a multi-objective fitness function problem can be presented as trying to determine the correct records of a set of $m$ parameters to a set of $n$ objectives. A multi-objective optimization model may be stated as follows:

Optimize [minimize/maximize]

$$F(\bar{x}) = \{f_1(\bar{x}), f_2(\bar{x}), ..., f_n(\bar{x})\} \quad (3.2)$$

subjected to

$$H(\bar{x}) = 0$$
$$G(\bar{x}) \geq 0$$
$$\bar{x} = (x_1, x_2, ..., x_m) \in X$$
In this case, the functions to be optimized (whether minimize or maximize) are the set of functions $F(\bar{x})$, where the vector $\bar{x}$ is the set of independent variables and $X$ is the parameter space. Functions $H(\bar{x})$ and $G(\bar{x})$ are the constraints of the model. In a multi-objective evolutionary algorithm, each $f_i(\bar{x})$ corresponds to the fitness function for a single objective. The purpose is to merge them to obtain a single fitness function, $F(X)$, considering with all objective and parameters. In real world, problem such optimization techniques discussed in this thesis, the solutions found; objective solutions even when they are conflicting, that is, when minimizing one function may worsen other functions. For example, minimizing BER and minimizing power simultaneously generate a divergence because of the single parameter i.e. transmit power, which affects each objective in a different manner. Obtaining the optimal set of decision variables for a single objective as minimize power, often outcome in a non-optimal set with respect to other objectives, e.g. minimize BER and maximize throughput. The optimal set for multi-objective functions placed is known as the Pareto optimal front [ZHOU et al., E. Zitzler and L. Thiele, pp. 257–271, 1999]. This front corresponds to the set of solutions that cannot be enhanced upon in any measurement. The results on the Pareto front are best and co-exist due to the trade-offs among the multi-objectives. A typical plot of a Pareto front, using a simple CR parameter state is shown in Figure 3.2. The y-axis represents the score of the single objective fitness function for BER in the case of several modulation types, while the x-axis is the score for the ratio of the energy per bit ($E_b$) to the noise power spectral density ($N_0$). The parameter $x$ corresponds to the decision vector of variable used as inputs to the fitness functions.
Here, transmit power and modulation was used as decision parameters. For every curve, as the fitness score for BER objective decreases, the value for the $E_b / N_0$ increases. This trade-off has to be made by using multi-objective optimization. The fitness functions used for this model are derived in Section 3.2. In this thesis, fitness functions using the defined set of parameters has been developed, that are used by CR engines to establish a single optimal transmission parameter result. In Figure 3.2, some parameter sets lie on the Pareto front, but the fitness function have to provide a search direction that directs the system to a single resolution. There are several methods that can be used to solve multi-objective problems using single-objective approximations. Some of them are weighted sum, $\varepsilon$-constraint, weighted metrics, Benson, and min-max, among others [Multi-Objective Optimization in Computer Networks Using Metaheuristics by Auerbach]. All of these methods try to find the
optimal Pareto front using different approximation techniques. This thesis uses a weighted sum optimization method, which consists of creating a single-objective model by weighing the $n$ objective functions by assigning a weight to each the functions. This method appears well with the CR development since it provides a suitable procedure for applying weights to the objectives. Through the weighted sum method, the multi-objective model (3.3) can be restated in the following way:

\[
\text{Optimize [minimize/maximize]}
\]

\[
F(X) = \sum_{i=1}^{n} w_i f_i(X) \quad (3.3)
\]

subjected to

\[
H(X) = 0 \quad G(X) \geq 0
\]

\[
0 \leq w_i \leq 1, \quad i = \{1, 2, \ldots, n\}
\]

\[
\sum_{i=1}^{n} w_i = 1
\]

In this case one can see that each function is multiplied by a weight ($w_i$) whose value must be found between 0 and 1. Also, the sum of all the weights applied to the function must be 1. An analysis of this type of solution shows that function $F(X)$ obtained from the sum is a linear combination of the functions $f_i(X)$. What the weighted sum method does exactly is find the points of the optimal Pareto front, which consists of all the optimal solutions in the multi-objective optimization, through
the combinations given by the weighted vector $W = \{w_1, w_2, ..., w_n\}$. For example, in the case of two objective functions would have the following equation.

$$F(X) = w_1 \cdot f_1 + w_2 \cdot f_2$$

Once the weighting each objective the value of weight is invariable, thus the search direction of the evolutionary algorithm is fixed. This is the proposed to find a single optimal result for a specified environment. However, varying the objective weighting then the fitness function will instantly invoke the evolutionary algorithm to navigate a new solution. For example, if a radio has to operate in a minimize BER mode. In this mode, the fitness function will give higher value to sets of parameter provided that a high transmit power, because the weight on the objective of minimize BER is the largest as shown in Figure 3.2. In the case when the radio detects low battery power, it switches the objective weighting to reproduce a minimizing transmitted power. This is made by decreasing the weights on other associated objectives at the same time as increasing the weight of the objective of minimize power. Once the weights change, the fitness function will immediately start giving higher scores to those parameter sets, which offer lower power transmission. This is the main characteristic that allows the objective weighting to order the radio goal state. DSA can be achieved by instantaneously switch operating goals by just modifying the vector of objective weighting.
3.5. **Cognitive Radio Objectives**

The environment of wireless communications requires some desirable objectives that the radio system would like to achieve. T. Christian James Rieser, reports using GA’s to resolve the optimization of wireless channel models and certain characteristics of the wireless communication system. Based on this work it was determined that a Fitness Measure (Fitness Function or Cost Function) required to be derived. This thesis defines four objectives for the fitness functions in order to direct the system to a best possible state are given in Table 3.3. Nowadays, in communication system, minimizing the BER is a common goal in wireless world. This objective minimizes the amount of errors with respect to the amount of bits being sent and improves the communications signal of the radio. Maximizing the throughput correspond to the system’s data throughput rate, this objective enhanced the system throughput.

**Table 3.3 Objective Function of CR.**

<table>
<thead>
<tr>
<th>Fitness objective</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize BER</td>
<td>Recover the on the whole BER/PER of the transmission environment.</td>
</tr>
<tr>
<td>Maximize Throughput</td>
<td>Increase the on the whole data throughput transmitted by the radio.</td>
</tr>
<tr>
<td>Minimize Power Utilization</td>
<td>Reduce the amount of power utilized by the system.</td>
</tr>
<tr>
<td>Minimize Interference</td>
<td>Reduce the radios interference contributions.</td>
</tr>
</tbody>
</table>

Minimize power utilization is easy to understand and is used to direct the CR to a situation of minimal power utilization. Minimizing interference objective are used to
avoid overlapping transmissions with other users that causes interference. The proposed CR engine model has been shown in Figure 3.3.

![Figure 3.2 Typical CR Engine Model](image)

Trade-off analysis between maximizing throughput, minimizing probability of bit error, minimizing power utilization and maximize spectral efficiency has been explored in chapter-4 of this thesis. The fitness function has to describe the trade-offs between each objective by ranking the objectives according to its importance. This thesis uses a weighted sum technique where each objective be given a weight on behalf of its importance [Multi-Objective Optimization in Computer Networks Using Metaheuristics by Auerbach, Cognitive Radio Technology by Bruce Fette, J. F. Hauris pp. 427–431]. This method is selected because of the simplicity of implementation of multi-objective optimization within the GA and PSO technique.

Last section defines four CR objectives for required system: reliability, throughput, power consumption and spectral interference. Next, defining the resultant objective functions of base-10 GA, PSO and hybrid (of these two) implementation in
order to direct the system to an optimal condition. In order to make easy the selection of the weights of the objective functions, normalizing each objective function score to the range [0, 1]. The implementations of four objective functions are as follows:

1) Minimize Bit-Error-Rate: The majority in wireless communication systems is to obtain an error free signal, or to minimize the BER of the transmission in order to reliability. Determining the theoretical BER based on numerous transmission parameters includes the transmit power, bandwidth, modulation type, modulation index and noise power. The most essential thing in determining the BER is the modulation and channel type in use. Every modulation and channel type combination uses a different method to conclude the BER of the system. One more vital factor in determining the BER of the system is the $E_b / N_0$ ratio. This ratio basically is a measure of the quantity of energy per bit to the quantity of noise power in the system, or on the SNR basis. To determine the $E_b / N_0$ ratio, denoted as $\gamma$, using the received power of signal, $S$ that is determined by the transmitted signal power and path loss, shadowing and multi-path fading as described in [Wireless communications, Anderea Goldsmith]. From $S$, one can get the quantity of energy per symbol $S / R_s (=E_s)$ by using the symbol rate $R_s$. For a alphabet of signaling with $M$ alternative symbols, each symbol represents $k = \log_2 M$ bits. $k$ is the modulation efficiency measured in bits/symbol or bits per channel use (bpcu ). The energy per bit ($E_b$) can be obtained by dividing by the number of bits in each symbol as

$$E_b = \frac{S}{R_s k} \quad \text{(W/b)} \quad (3.4)$$
The single-sided noise power spectral density (W/Hz) is calculated by Boltzmann’s equation.

$$N_0 = k_b T \quad (J) \quad (3.5)$$

$$N = N_0 B \quad (3.6)$$

Where \(k_b = 1.38 \times 10^{-23} \text{J/K}\) (Boltzmann’s constant), \(T\) is the noise temperature (290K), \(B\) is bandwidth of the channel, and \(N\) is the total computed noise power.

The ultimate equation for the value of \(\gamma\) that the BER functions utilized is given by:

$$\gamma = \frac{E_b}{N_0} = 10\log_{10}\left[\frac{S}{R k N_0}\right] = 10\log_{10}\left[\frac{S}{R k N}\right]$$

$$= 10\log_{10}\left[\frac{S}{N}\right] + 10\log_{10}\left[\frac{B}{R k}\right] \text{(dB)} \quad (3.7)$$

The following equations give the BER of BPSK, M-ary PSK and M-ary by assuming an AWGN channel model with gray-coded bit assignment [J. G. Proakis, Digital Communications].

For a BPSK signal constellation, the bit error probability is given as

$$P_{be} = Q\left(\sqrt{\gamma}\right) \quad (3.8)$$

For M-ary PSK, the bit error probability is defined as

$$P_{be} = \frac{2}{k} Q\left(\sqrt{2k\gamma \sin \frac{\pi}{M}}\right) \quad (3.9)$$
And M-ary QAM, the bit error probability is given as

$$P_{be} = \frac{4}{k} \left(1 - \frac{1}{\sqrt{M}} \right) Q\left(\sqrt{\frac{3k}{M-1}}\gamma\right)$$

(3.10)

Lastly, Probability of Packet-error (PER) is given as

$$P_{pe} = 1 - (1 - P_{be})^L$$

(3.11)

Suppose that the bit errors are independent of each other. For small bit error probabilities, this is approximated as

$$P_{pe} \approx (P_{be})^L$$

(3.12)

Therefore, probability of bit-error can be determined from given probability of packet-error using (3.11) and (3.12).

One feasible objective function for defining the reliability of the system is:

$$f_{\text{min, ber}} = 1 - \frac{\log(0.5)}{\log(P_{be})}$$

(3.12)

Where $P_{be}$ is the average probability of bit error (BER) for a specified modulation system over $N_c$ independent sub-carrier. This objective function, which was originally proposed by [Newman et al.], however, it does not fit well with the common QoS requirement which is based on a maximum acceptable BER or PER and over this threshold, the communication is interrupted. In this concern, a objective function for the reliability of the transmission ensures that PER is equal to or lower than a target
PER represented as $\text{PER}^*$ [Alexandre de Baynast et al., Pages 778-794]. However, equation of this objective function still having error and modified specifically as,

$$
 f_{\text{min} \_ \text{ber}} = \begin{cases} 
 1, & \text{if } \frac{\log_{10}(\max(\text{PER}^*, \text{PER}))}{\log_{10}(\text{PER}^*)} \geq 1, \\
 1 - \frac{\log_{10}(\max(\text{PER}^*, \text{PER}))}{\log_{10}(\text{PER}^*)}, & \text{otherwise}.
\end{cases}
$$

(3.13)

This objective function penalizes if $\text{PER} > \text{PER}^*$ and $f_{\text{min} \_ \text{ber}} = 0$, if $\text{PER} \leq \text{PER}^*$, also guarantee that value of the $f_{\text{min} \_ \text{ber}}$ will be fall in range $[0, 1]$ and it was not in the case of paper [Alexandre de Baynast et al., Pages 778-794].

![Figure 3.4](image-url) A plot of bit-error-rate vs. packet-error-rate using (3.11).
However, choose $10^{-5}$ to be the best-case BER in order to zero PER as shown in Figure 3.4 and all investigational values seen lower this value will be rounded up to $10^{-5}$.

2) Maximize Throughput: This increases the overall data throughput transmitted by the radio. At the physical layer, the pulse duration $T$ and that its bandwidth $B$ is approximately equal to the reciprocal of $T$. Thus, $B = I/T$ and, $T = k/R_b = \log_2(M)/R$, it is follow that,

$$B = \frac{R_b}{\log_2 M} \quad (3.14)$$

Therefore, as $M$ is increased, the channel bandwidth required, when the bit rate $R_b$ is fixed, decreases. For multi-carrier signal $T$ can be expressed in number of bits per symbol period as $T = \sum_{i=1}^{N_c} \log_2(M_i) / N_c$, where $N_c$ indicate the total number of channels that SU operates on it, where $i = 1, \ldots N_c$, and $N_c$ being the upper limit of channels that a SU will be operate on, $M_i$ is the order of modulation emitted on sub-carrier $i$, $M_{\text{max}}$ is the maximum modulation order with typical values 64 or 256 in wireless networks. $M_i$ can take values from 1 to $M_{\text{max}}$ with 1 special case occurring when sub-carrier $i$ is shut down. $M_i = 1$ means that the rate $\log_2(M_i)$ is equal to zero; no information is transmitted. In this particular case, the corresponding transmission power $P_i$ is set to zero. In this particular, $0 \leq T \leq \log_2 M_{\text{max}}$, where the value $\log_2(M_i)$ is achieved when all sub-carriers are loaded with symbols modulated with the largest available modulation order. Therefore, the objective function for the throughput is simply:
\[
    f_{\text{max\_throughput}} = 1 - \frac{1}{N_c \log_2(M_{\text{max}})} \sum_{i=1}^{N_c} \log_2(M_i)
\] (3.15)

The function \( f_{\text{max\_throughput}} \) is equal to 0 when all sub-carriers transmit with largest modulation order and equal to 1 when all sub-carriers are switched off.

3) Minimize Power Consumption: This objective function decreases the amount of transmission power and given by

\[
    f_{\text{min\_power}} = \frac{1}{N_c P_{\text{max}}} \sum_{i=1}^{N_c} P_i
\] (3.16)

Where \( N_c \) indicate the total number of channels that SU operates on it, where \( i = 1, \ldots, N_c \) where \( N_c \) indicate the total number of channels that SU operates on it. \( P_i \) is the transmission power on sub-carrier \( i \) takes values range \([P_{\text{min}}, P_{\text{max}}]\) and \( P_{\text{max}} \) is the maximum possible transmission power for a single sub-carrier. \( P_i \) can takes values zero, i.e., no transmission on sub-carrier \( i \) if the channel fading coefficient in this band is smaller than a pre-determined threshold [Alexandre de Baynast et al., Pages 778-794].

In other words, \( f_{\text{min\_power}} = \begin{cases} 1, & \text{all subcarriers are transmitting with } P_{\text{max}}. \\ 0, & \text{all subcarriers are transmitting with } P_{\text{min}}. \end{cases} \)

4) Minimizing interference: This is an essential objective in shared frequency bands. For example, this objective may be given a high weighting by a SU that operates spectrum in a PU band. Here, the PU has main concern in a particular band of frequency and on the other hand SUs are permitted to transmit in the band given causing no interference to the PUs. Radio parameters such as bandwidth (B) and transmit power (P) are used to determine the estimated amount of spectral interference
produced by transmission. Overlapping transmissions with other users causes interference. Ideally, to compute the total interference, integrating over the spectral bandwidth that transmitted, and get the total power of overlapping transmissions. In this thesis, it has been assumed uniform power transmission over the bandwidth of transmission permitting to obtain the interference equation given by,

\[ f_{\text{interference}} = P \times B \]  \hspace{1cm} (3.17)

As increase in interference the bandwidth increases and, interference is increases as the transmit power of the transmitter increases. Thus, increased in spectral leakage and more power interfere with another system. The normalized spectral interference is given by,

\[ f_{\text{min\_interference}} = \frac{1}{N_c \times P_{\text{max}} \times B_{\text{max}}} \sum_{j=1}^{N_c} (P \times B) \]  \hspace{1cm} (3.18)

This objective function is defined as, if \( f_{\text{min\_interference}} \approx 1 \), then subjected to maximum interference, when \( f_{\text{min\_interference}} = 0 \) then, there is no interference or minimum interference.

3.6. Multi-Objective goals

The weighted sum approach permitted to merge the single objective functions into one cumulative multi-objective function. Equation (3.19) illustrates that each objective is multiplied by a weight \( w_i \) and added simultaneously to give a single value that are equivalent to the value of a parameter set. The weighted sum approach
attempts to minimize the sum of the absolutely normalized, weighted, single objective scores of the parameter set solution. The multi-objective function for multi-carriers can be obtained in forms of single objection function by use of weighted sum approach that provide single scalar value using four objectives (3.13), (3.15), (3.16) and (3.18) as,

\[
F = w_1 \cdot f_{\text{min\_ber}} + w_2 \cdot f_{\text{max\_throughput}} + w_3 \cdot f_{\text{min\_ower}} + w_4 \cdot f_{\text{min\_interference}} \quad (3.19)
\]

Where, \(w_1, w_2, w_3, w_4\) are the weighting values that decide the search direction for the evolutionary algorithm (EA). This technique suits the cognitive radio state as shown by Newman et al., since it provides a suitable process for applying weights to the objectives. As the weighting for each objective is constant, the search direction of the EA is unchanging as example shown in Table 3.4. This is the preferred property when demanded to discover a single optimal solution for a particular environment. Varying the objective direction of the fitness function needs just a simple change of the weighting vector.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Weight Vector ([w_1, w_2, w_3, w_4])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize BER (Emergency Mode)</td>
<td>[0.70, 0.10, 0.10, 0.10]</td>
</tr>
<tr>
<td>Maximize Throughput (Multimedia Mode)</td>
<td>[0.15, 0.60, 0.10, 0.15]</td>
</tr>
<tr>
<td>Minimize Power (low power mode)</td>
<td>[0.10, 0.20, 0.55, 0.15]</td>
</tr>
<tr>
<td>Minimize Interference (DSA Mode)</td>
<td>[0.10, 0.20, 0.10, 0.60]</td>
</tr>
</tbody>
</table>

Using the weight vectors shown in Table 3.4 and CR engine has been generated base-10 GA and PSO convergence results by use of the fitness functions and is presented in Chapter 4.
3.7. Summary

This chapter explores a precise list of common parameters for CR. These parameters contain environmentally considered parameters from sensors inside the CR system, and operation of internal information on conditions that measurement concerning the internal state of the radio. This information is used in combination with the CR objectives to decide the suitable transmission parameters to use by SU. A multi-objective problem contains complexities while all objectives are trying to be achieved at once upon a time. The main complexity is to find the trade-offs between the parameters of the multi-objectives. This work defines four performance CR objectives for a SU in which various objectives overlapped as consider to maximizing their performance. All fitness function used in this thesis to optimize QoS performance has been listed in the Table given below.

<table>
<thead>
<tr>
<th>Fitness Function</th>
<th>Function Derivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize BER</td>
<td>[ f_{\text{min_ber}} = \begin{cases} 1, &amp; \frac{1}{\log_{10}\left(\max(PER', PER)\right)} \ \frac{1}{\log_{10}\left(\max(PER', PER)\right)}, &amp; \text{otherwise.} \end{cases} ]</td>
</tr>
<tr>
<td>Maximize Throughput</td>
<td>[ f_{\text{max_throughput}} = 1 - \frac{1}{N_i \log_2(M_{\text{max}})} \sum_{i=1}^{N_i} \log_2(M_i) ]</td>
</tr>
<tr>
<td>Minimize Power Utilization</td>
<td>[ f_{\text{min_power}} = \frac{1}{N_c P_{\text{max}}} \sum_{i=1}^{N_c} P_i ]</td>
</tr>
<tr>
<td>Minimize Interference</td>
<td>[ f_{\text{min_interference}} = \frac{1}{N_c \times P_{\text{max}} \times B_{\text{max}}} \sum_{i=1}^{N_c} (P \times B) ]</td>
</tr>
<tr>
<td>Single Function for multi objective</td>
<td>[ F = w_1 \cdot f_{\text{min_ber}} + w_2 \cdot f_{\text{max_throughput}} + w_3 \cdot f_{\text{min_ower}} + w_4 \cdot f_{\text{min_interference}} ]</td>
</tr>
</tbody>
</table>