CHAPTER Four

Adaptive equalizations for sensitivity boosting

10 Introduction

The wireless channel environment is very complex due to several reasons, like multipath, propagation loss, fading, multi-user interference, co-channel interference, adjacent channel interference and noise signal. The mobile wireless channel becomes further complex due to the user mobility. The Doppler Effect becomes prominent, when user becomes mobile. In these scenarios, the air channel plays pivotal role, as its characteristics mainly influences the signals, which propagate through it. Apart from these above mentioned issues, the signal fading statistics make the mobile wireless channel extremely unpredictable [21] and varies time to time. On top of fading, noise, interference and attenuation factors, the quality of a wireless link between the transmitter and receiver is highly dependent on the mobile environment, radio propagation parameters and air channel’s characteristics etc. Also, Inter Symbol Interference (ISI) plays a significant role, especially, if the symbol duration (T) is shorter than channel delay time. Generally, the multi-user, mobile wireless environments are broadly classified into two categories:

(1) Sensitivity limited Scenarios: In this scenario, the received signal power at the receiver circuit is very low e.g. received signal is very feeble and the signal is mainly influenced by the AWGN noise in the receiver circuit and fading characteristics of the propagation channel.
Depending on the delay characteristics of the propagation channel, the sensitivity limited scenarios can be classified into two categories:

(a) **Non-delayed channel**: in this case, channel delay is less than one symbol period.

(b) **Delayed channel**: in this case, channel delay is more than a symbol period.

(2) **Interference limited Scenarios**: In a high interference scenario, the carrier to interference (C/I) ratio reduces. This scenario is different from sensitivity scenario, as described above. Here, though the desired signal power level might be high or the received signal level (RSSI) is high, but as the received input signal mixed with the interference signal (I), so correct demodulation and decoding of data becomes much difficult. In this case, depending on the nature of the interference, the interference limited scenarios can be broadly divided into two categories:

(a) **Co-Channel Interference (CCI)**: If the interferer signal’s frequency is same as the desired carrier’s frequency, then the interferer is called as co-channel interferer. Generally this happens because the same frequency channel is re-used in a distant cell. This type of interference is considered as colour noise.

(b) **Adjacent channel Interference (ACI)**: If the interferer signal’s frequency is next to the desired channel’s frequency, then the signals from nearby frequency channel (adjacent channel) leak into the desired channel. This type of interference is called as the adjacent channel interference.

As discussed above, there could be several types of channel conditions based on the type of noise, fading and interference characteristics. That’s why, only one type of channel estimation and equalization technique will not be appropriate for all these different types
of channel propagation and interference scenarios. Some of these techniques provide better performance gain in co-channel interference condition, whereas those degrade the receiver performance in a sensitivity conditions. Similarly some techniques enhance the BER performance in some specific channel conditions, but degrade the performance in some other channel propagation conditions. Also, running wrong or not appropriate algorithms in an inappropriate channel condition causes un-necessary processing power (MIPS) wastage and that leads to battery power wastage, without any performance gain. That’s the reason, to get the best out of everything; there is a need of environment or channel condition detectors. This will adaptively detects the channel condition and then adaptively enable the corresponding best appropriate algorithms / solutions to get the best performance in that scenario [38].

11 Channel Condition Detection Techniques

In GERAN (GSM, GPRS and EDGE systems) mobile phone receiver, most commonly the single antenna interference cancellation (SAIC) algorithm is used in interference limited scenario, that means when the input signal is dominated by the interferer signal or, the Carrier to Interference ratio (C/I) is lower. The SAIC algorithm uses whitening process, which improves the CCI and ACI performance, but it might reduce the sensitivity performance at low signal conditions due to unnecessary whitening process, which degrades the SNR. So, generally in sensitivity scenarios e.g. low signal condition, another type of channel equalizer is used for processing. That means, when there is low interference signal present in the received signal e.g. high CIR (carrier to interference ratio), whitening is bypassed to avoid reducing of SNR (in a sensitivity scenario). So, to
take the advantages of both, there is a requirement to dynamically detect the interference or sensitivity scenario and selecting or adjusting the equalizer type accordingly. So, in interference limited channel scenario receiver algorithm will enable SAIC equalizer, whereas in sensitivity limited scenario the receiver will enable the default equalizer (non-whitening).

On the other hand, if the detected channel type is adjacent channel interference (ACI), then the input digital [I-Q] samples will be passed through a narrower Low pass filter (with bandwidth < 200 KHz for GSM system) to eliminate the out of band signals, before the signal is passed for channel estimation and equalization, which will help to enhance the Adjacent Channel rejection performance. So, first the equalizer switching algorithm has to detect the ACI scenario dynamically and if ACI condition is detected then only enable the narrow band filter for performance boosting.

As discussed earlier, In case of a delayed sensitivity channel environment, generally the channel taps spans over more than 3 taps, in such case; the Maximum likelihood sequence estimation (MLSE) equalizer with more number of channel taps is a better choice to handle multi-path delays. So, the channel length or channel type (delayed or non-delayed) has to be detected quickly by the channel condition detection algorithm and then based on that detected channel type, the equalizer switching will select the channel tap lengths (3 or 7 taps) and MLSE taps accordingly. That indicates first the channel type detection switch has to dynamically detect the channel type and after that it has to adjust or select the channel tap length and enable MLSE for higher number of taps, instead of keeping more taps in the feedback path in Decision Feedback Sequence Estimation (DFSE) type of equalizer [39].


11.1 Description of the Detection Algorithm

As discussed above, the proposed algorithm should be doing two tasks:

(a) Channel environment detection (Sensitivity, CCI, ACI…detection)

(b) Adaptive filtering and equalizer processing

11.1.1 Dynamic Channel Environment Detection method

Depending on the received signal strength (RSSI), presence of interference signals (CCI, ACI) and channel delay characteristics (3 taps, 7 taps), the wireless channel can be broadly classified into four categories: co-channel (CCI), adjacent channel (ACI), sensitivity-delayed and sensitivity-non-delayed.

The channel environment detection module has two parts:

(a) Channel type detection: this sub-module will detect, whether the channel is Sensitivity limited (AWGN) or ACI or CCI dominated

(b) Delayed or non-delayed channel detection: if the detected channel type is sensitivity limited, then this sub-module helps to detect the channel length to indicate whether it is a delayed (> 3 taps) or non-delayed channel.

11.1.2 Detection of Channel Type

In this work, as described below one simple method is proposed to dynamically detect the channel condition. The received complex-valued, baseband, symbol-spaced signal can be modeled as:
\[ r(n) = \sum_{k=0}^{N} h(k)s(n - k) + I(n) \]

Where, \( s(n) \) is the transmitted symbol,
\( h(k) \) is the channel response, where \( h(k)'s \) are the coefficients of the baseband channel,
\( I(n) \) is un-desired signal. \( I(n) \) includes white noise (AWGN) as well as coloured (correlated) noise sequence including CCI, ACI, and multi-path components.

Based on the received sequence and known transmitted bit sequence (which is actually the Training sequence code (TSC) in GSM), the channel impulse response \( h(k) \) is computed. The auto-correlation of the signal is defined as:
\[
\rho_{vv}(k) = E\{I(n) I^*(n-k)\}.
\]

Let’s consider that the undesired / unwanted signal \( I(n) \) is white, that means the auto-correlation of \( I(n) \), \( \rho_{vv}(k) = \delta(k) \), the ML estimate (which is the optimal estimate) of \( h(k)'s \) is the least squares estimate (LSE). But, when the noise \( I(n) \) is not white (i.e. \( \rho_{vv}(k) \neq \delta(k) \)) the least-squares estimate is not the Maximum-Likelihood (ML) estimate of \( h(k) \).

In any typical cellular mobile receiver system, the undesired signal \( I(n) \) can be modeled as the sum of three signals (CCI, ACI and AWGN) as below which is passed through the received filter:
\[
I(t) = [I_{CCI}(t) + I_{ACI}(t) + I_{WN}(t)] * p(t) \]

And \( I(n) = I(n \times T_{symbol}) \).

Where, \( p(t) \) is the analog receive filter, \( I_{ACI}(t) \) is the analog adjacent channel interferer (ACI) before the received filter, \( I_{CCI}(t) \) is the analog co-channel interferer (CCI) signal before the received filter and \( I_{WN}(t) \) is the additive Gaussian thermal noise (AWGN) before the received filter.
From this above composite signal, I(n) is obtained by sampling I(t) at every $T_{symbol}$ seconds. $I_{CCI}(t)$ or $I_{ACI}(t)$ can be colored so, I(n) might become colored. On top of that, if $p(t)$ is not a Nyquist filter then I(n) might become colored. Generally, I(n) can be colored, and the colour of the disturbance might change from one received burst to another received burst that means over the time. In case of coloured noise, if the ML estimate is used then it will be not appropriate as, the ML estimate of the channel coefficients is not the least-squares estimate in case of coloured disturbances. In this work, it’s assumed that the auto-correlation of the disturbance belongs to a finite set of candidate auto-correlations. It is also assumed that this auto-correlations set and the whitening filter corresponding to each of these auto-correlations is known apriori. Now, let’s enumerate these candidate auto-correlations by $\{p^i_{un}(k)\}_{i=1}^{N}$, and represent the corresponding whitening filters as $\{h^i(k)\}_{i=1}^{N}$. Then we find out the channel estimation for each auto-correlation and can be represented as, $h^i(k)$ which minimizes the Maximum-Likelihood criteria considering that this auto-correlation is the right one. Then, we need to select the Channel estimate and auto-correlation estimate among these N pairs of channel estimates and auto-correlation estimates, which minimizes the ML criteria in the above equation. In the receiver, it is assumed that two pass channel estimation is used and in the first pass channel estimation, a fixed whitening filter is selected to cater to ACI, CCI or AWGN scenarios, depending on the power of the residual noise remaining once the training sequence (e.g. pilot bits) signal part is filtered with each of these three type filters. According to above discussion, three pre-calculated whitening filter taps in three noise models with could be:

a) White noise (AWGN)
b) Co-channel interference (CCI),

c) Adjacent channel interference (ACI)

So, during the processing the following steps are performed in sequence to detect which noise-model is best suitable (or most appropriate) for the received input signal’s processing:

(1) The dc offset is estimated and then compensated. Next, the I,Q samples are normalized and then channel estimation is performed on the received dc compensated normalized [I-Q] samples. At the first stage, the simple channel estimation is performed by using only 3 channel taps.

(2) Next, the reference synchronization (pilot or training) sequence (s’) and channel estimate (h) are convolved to get x^, estimated synchronization(training) sequence. The noise samples (ns) are computed by subtracting x^ from the received synchronization samples (r) as given in the below equation.

\[ x^\ = \ s’ \ast h \]

\[ ns = r - x^; \]

(3) The receiver should have three pre-designed filters, made for ACI, CCI and AWGN. Upon filtering using the pre-calculated whitening filter, the receiver computes the power residues of noise samples- that will provide three power residues. The minimum out of these three values- will indicates - whether it is a Sensitivity scenario or CCI scenario or ACI scenario. Sensitivity is indicated as 0, CCI as 1 and ACI as 2.

(4) The output from the above detection will be an index value, which indicates whether the current burst experiences the channel as white noise (=0), CCI (=1), or ACI (=2) type
disturbances. Depending on the detected index value, the present channel type will be set to Sensitivity or CCI or ACI.

(5) The wireless channel conditions or channel environment may change dynamically from one burst to another burst, so, some sort of averaging might be required. The current detected channel type required to be stored e.g. remembered for detecting the long-term averaging of channel type value consideration. This is taken care by introducing a forgetting factor variable and using the forgetting factor the average channel type is selected. Then that average channel type will indicate the channel environment at any given point of time [38].

11.1.3 Detection of Channel Length

In the previous section we have discussed about the mechanism for channel type detection. After the channel type detection, the receiver algorithm requires to detect the channel length (L) that indicates whether it’s a time delayed or non-delayed channel. For channel length estimation the following steps will be executed:

(1) To find the scaled squared error- perform a ‘4-tap’ channel estimation; where the scaled error is product of estimated error and the modified Akaike Information Criterion (AIC) factor.

$$\text{Scaled\_sqerror1} = \text{4-tap channel estimation error} \times \text{Akaike Information Criterion (AIC) factor}$$

(2) To find the scaled squared error- perform a ‘7-tap’ channel estimation; where the scaled error is computed by multiplying the error by the modified Akaike Information Criterion (AIC) factor.
Scaled_sqerror2 = 7-tap channel estimation error * Akaike Information Criterion (AIC) factor

(3) Next, the minimum error from both the above computations are compared and the channel length is decided whether it will be 4-tap or 7-tap based on the one which is having the minimum squared error

Channel_length = 4-tap if Scaled_sqerror1 = min (Scaled_sqerror1, Scaled_sqerror2)

Channel_length = 7-tap if Scaled_sqerror2 = min (Scaled_sqerror1, Scaled_sqerror2)

(4) A variable is used to indicate the channel length. The channel length is set to ‘1’ or ‘0’ based on whether the current detected channel length is 7 or not. From this an average channel length for channel length 7 is derived using an exponential averaging.

(5) Then it is decided on the final channel length, whether delayed or non-delayed type by comparing the averaged variable with a threshold.

A generalized block diagram of the mobile receiver with channel estimation block is shown in figure 4.2 (a). Here as discussed above, a model is proposed for dynamically detecting the wireless channel environment propagation conditions. Once that is detected, then it adaptively selects the right equalization techniques [38] based on the detected channel type. The block diagram of this model is shown in figure 4.2 (b).

11.1.4 Adaptive Switching control

In the previous section, it is discussed how the channel condition is detected, now, we require a switching mechanism to select the right equalizer according to the channel type
detected. The following switching mechanism is implemented for equalizer switching and hence obtaining the best performance.

(a) If the detected channel condition is sensitivity scenario, the SAIC (single antenna interference cancellation) module processing is bypassed.

(b) If the detected channel condition is interference (CCI/ACI) scenario, the SAIC module is executed.

(c) If the detected channel condition is sensitivity scenario (low RSSI conditions), noise shaping filter is enabled.

(d) If the detected channel condition: ACI scenario and Sensitivity scenario then a Narrow Band Low pass filter is enabled.

(e) The channel length control signal is used to override the selection between 4-tap and 7-tap channel estimate to provide the final estimate.

(f) If the channel type detected is delayed channel, then enable the technique to increase the tap length to be used in MLSE equalizer.

Figure 4.6, shows the proposed receiver architecture with this environment detection and adaptive switching and equalization modules [38].

12 Method for computing true Received Signal Strength (RSSI) value

As discussed earlier, the equalizer can be also switched based on the received signal strength. That means if the received signal strength is low, then generally, whitening can be bypassed on the other hand, if the received signal condition is high then whitening
can be selected for processing. So, measuring the true received RSSI is very important, especially it is also used to report to the network about the signal strength (RXLEV).

In a FDMA system like GSM, where the same frequencies are reused again in the distant cell, so the presence of co-channel interference in the serving cell periphery is very high. This has become more severe recently due bad cell planning and smaller cell sizes as shown in figure 4.1 (a). So, due to this presence of high co-channel interference signal in the desired cell’s measured RSSI there will some contribution from the distant neighbour cell of same frequency carrier. So, the measured RSSI by the MS is not for its own signal strength but also for the other distant neighbour’s carrier strength.

![Diagram](image)

Figure 4.1 (a), RSSI measured from different GSM cells

**RSSI scattering distribution co-efficient estimation:**

This is a new method proposed here. In this method there is no need of any known data sequence (TSC) to be present in the received I,Q samples. Generally, it is difficult to open the receiver RF window at a defined time window to receive TSC data part due to several issues. So, this method is free from that requirement. Here, the scattering co-efficient of the I,Q sample pairs are measured from the average position and based on that the presence Noise and Interference power proportion is estimated as shown in figure 4.1 (b). Then that I+N power is subtracted from the measured total RSSI. Generally, when
the presence of noise or interference is less in the received signal, then the I,Q pairs are not much scattered from the mean position that means in the constellation diagram these I,Q points will not be very scattered, rather these will be well clustered around the average radius circle. This is true for GMSK type of constant modulation techniques. GSM system uses this. So, this principle is used here to estimate the total noise and interference power in the received I,Q samples.

To measure true RSSI, we need to estimate the I and N power in the measured RSSI and subtract that to get true RSSI of the measured carrier as shown in below equation:

\[ \text{RSSI}_{\text{true}} = \text{RSSI}_{\text{total}} - (I + N). \]

Generally the RSSI (total) is computed as below:

\[ \text{RSSI}_{\text{total}} = \frac{1}{M} \sqrt{ \frac{1}{M} \sum_{m=0}^{M-1} (I(m)^2 + Q(m)^2) } \]

Where M is the total number of samples in the burst and m is the sample number. A signal strength value, for each signal sample, m, also known as RSSI\(_m\), may be measured according to:

\[ \text{RSSI}_m = \sqrt{I_m^2 + Q_m^2} \]

There will be M such RSSI\(_m\), as there are M received signal samples. The normalized average signal strength value, also called RSSI\(_{m,\text{norm}}\), may be calculated by dividing

\[ \text{RSSI}_m \] by RSSI\(_{\text{avg}}\) according to:

\[ \text{RSSI}_{m,\text{norm}} = \sqrt{\frac{I_m^2 + Q_m^2}{\text{RSSI}_{\text{avg}}}} \]

The standard deviation of the amplitude of each signal sample may be measured from the average signal strength value, normalized to unity:
Std-deviation = \Delta = \sqrt{\frac{1}{M} \sum_{m=0}^{M-1} (1 - \text{RSSI}_{m, \text{nom}}(m))^2}

= \beta \cdot (P_{\text{interference+noise}} / \sqrt{M}).

Where, \beta is a constant factor which can be derived empirically. Then estimated Std-deviation value is mapped to C/(I+N) value and then from this the true RSSI value is computed.

![Diagram showing scattered I,Q pairs and average RSSI circle.](image)

**Figure 4.1 (b), Scattered GMSK I,Q sample pairs**

### 13 Simulation Result

The simulation result for TCH Full rate (TCH/FS) logical channel in static wireless channel conditions and sensitivity scenario is shown in figure 4.8. In this case, as shown
in the figure, the estimated average channel type value most of the time it rightly indicates about sensitivity scenario as shown in figure 4.7, and also the channel length average value shows as 4, that confirms that it is detecting as a static channel.

The achieved BER curve with the new detection and selection algorithm shows the improvement, which can be noticed in figure 4.8.

- The algorithm detects the right channel environments with an accuracy of around 90%.

- The new proposed algorithm provides an overall performance gain of around 0.7 dB for Sensitivity cases and around 0.1 dB for all others (CCI, ACI, DARP cases).

- This proposed method does not have any side effects, like degrading the performance for some other channels or propagation conditions.

- This proposed method also helps to save processing power e.g. processing cycles. The overall cycles or power saving is greater than 5000 cycles [38], [39].

14 Conclusions

This proposed method provides several advantages as mentioned below.

(a) Using this technique, Mobile receiver can dynamically detect the wireless channel propagation scenario – whether it is sensitivity-delayed channel or sensitivity-non-delayed channel or co-channel interference scenario or adjacent channel interference scenario.

(b) Based on the detected channel scenario, the proper signal processing algorithm will be enabled to get maximum BER performance.
(c) If no interference scenario is detected then SAIC is disabled irrespective of the RSSI level, which will help to reduce the processing power (MIPS) and electrical power consumption of the system. Because earlier at the higher RSSI level all the time SAIC was enabled.

(d) Static Sensitivity performance is improved by using sensitivity optimized filter in a scenario where sensitivity non-delayed channel is detected. This does not impact any other channel condition's performance e.g. sensitivity delayed channel, CCI or ACI performance.

(e) This improves the SAIC performance to the extreme limit possible from the used algorithm. As the detector detects the proper CCI channel condition, and accordingly the SAIC algorithm is applied as when it is detected, that helps to achieve maximum performance from SAIC algorithm.

(f) This helps to improve the performance of sensitivity delayed channel (like HT-100), by selecting proper channel tap lengths and increasing the number of MLSE taps [38].
Figure 4.2 (a), a general block diagram of a typical mobile receiver

Figure 4.2 (b), Model to identify the channel type and channel length
Figure 4.3, Frequency response of the filter used for ACI scenario

Figure 4.4, Frequency response of the filter used for CCI scenario
Figure 4.5. Switching control in the receiver signal processing chain
Figure-4.6, Receiver diagram with environment detection and adaptive switching and equalization modules
Figure 4.7, Channel type and channel length identification

Figure 4.8 BER improvement plot in TCH/FS, sensitivity, static channel scenario
15Publications and Patents

The above obtained results are published in [38] and filed US patent in [33]. Another international patent (PCT/EP2013/076391) is filled on true RSSI detection method as described in section 12 above.