ECE 708

Technologies for Long-Term Evolution of

Wireless Communications Networks

PROJECT REPORT

DECODERS: Successive Interference Cancellation (SIC), Minimum Mean Square Error (MMSE), Message Passing Algorithm (MPA)

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Abstract:

All signals transmitted are encoded before being sent onto the channel and they need to be decoded using a decoder at the receiver in order to get back the original signal. Along with the advancement in technology and ever rising demand of the users, there is an inevitable need for novel and efficient decoders. Some of the decoders are Message Passing Algorithm (MPA), Minimum Mean Square Error (MMSE), Successive Interference Cancellation (SIC). These concepts, though developed long ago, needed sophisticated technology in order to be implemented efficiently. The significant developments in the field of computer processing and electronics has allowed these techniques to resurface into the communication domain. In this report we will discuss about the decoders in brief, algorithm, performance parameters and working of these three decoders viz. MPA, MMSE, and SIC. We will also discuss the applications of these decoders in the recent technologies used for 5G communication such as LPDC (Low density parity codes), SCMA (Sparse Code Multiple Access), PDMA (Pattern Division Multiple Access), and MIMO (Multiple-input Multiple-output) systems.

Introduction:

The communication channel is accessible by everyone as it is a free space, and open and everything is transmitted via electromagnetic waves. Because of this, it is quite possible for anyone to tap into our information that is being transmitted if there were not any form of security to protect the data that is being transmitted. This is one of the main reason why we require encoding and decoding procedure. Also, the channel can introduce errors in the message which is transmitted from source to the destination. To identify and remove such errors, encoding and decoding is used. Our main job in encoding is to change the data being transmitted from one form to another using certain criteria and rules, in order to create a complex message format. The inverse process is repeated at the receiver to perform the process of decoding. It has to be understood that the process of communication is continuous, that is the information source is continuously encoding the new information and transmitting it into the channel while the receiver is responsible for decoding the encoded information. It is necessary that the transmitted message is clear, in order for the receiver to be able to decode the message despite the presence of errors that are introduced by the channel.

In the years, there has been significant improvements in the communication domain. The ever rising demand for faster, efficient, and reliable communication system has propelled the scientists to make better use of the existing channel. This in-turn places a very taxing constraint on the transmitters and receivers, needing them to perform to their very best, specifically the demand on the receivers is ever rising. The channel adds errors and interferences to the signal in the form of noise and it is the duty of the receiver to be optimal enough to recognize the errors and provide a proper decoding of the transmitted message. The decoding procedure has seen significant improvements over the years and we will look at few famous decoding procedures and how these new technologies are suitable for the modern LTE systems. Most of the technologies implemented, were invented quite earlier, but couldn't be implemented owing to the lack of development in the processing capability of the computers. But now due to the advancement in the computational power and capacity, these techniques are being used once again in the new technology for 5G communication.

Successive Interference Cancellation (SIC) Decoder:

Any communication channel is posed with the problem of interference, where there is always the presence of some form of disruption as the signal propagates. This disruption is further more alleviated with increase in demand from the users, as the scientists are trying to fit more signals into the channel at the same time. This inevitably gives rise to interference such as Co-channel, Adjacent channel, Inter symbol Interference to name a few. As the demand is ever rising, we are posed with the necessity to find more efficient receivers which can operate even in the presence of interference with significant accuracy, and reliability. Hence the need to use decoders with the capability to process signals with significant interference and still have the ability to separate each and every signal.

We shall look how SIC is used in decoding a signal disrupted with co-channel and adjacent channel interference.

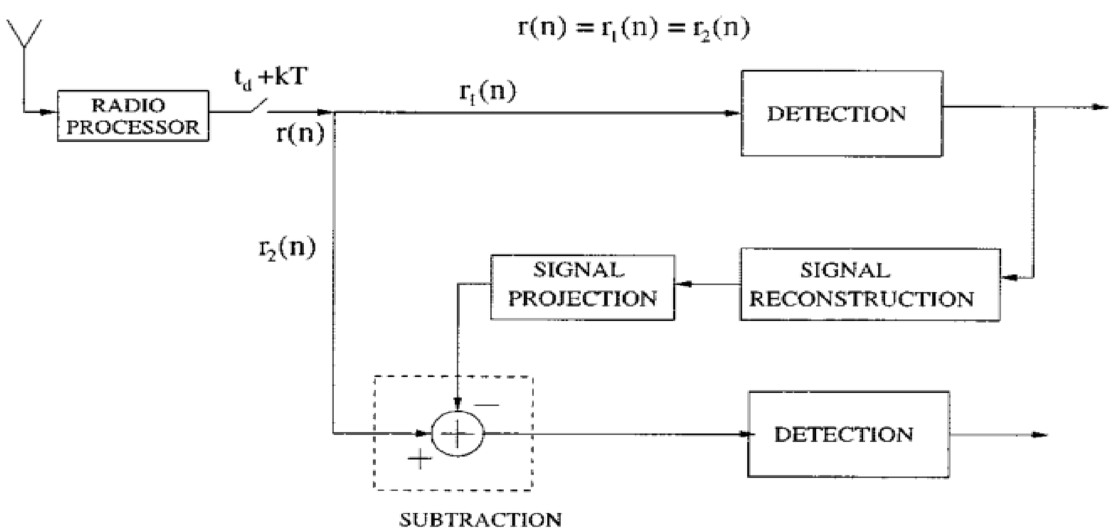

Fig. 1 Successive Cancellation.

Fig. 1 shows the stages involved in detection of a signal that has co-channel interference, here the received signal at the receiver is baseband signal r(n) which contains both the signal and the co-channel signal. We sample the received signal at the same time intervals. In order to successfully remove the interfering signal from the received signal, we try to estimate the stronger signal of the two. This is then processed again and reconstructed later on subtracted from the input signal there by enabling the system to process the weaker signal with better reliability. Then the process is repeated again, but with the weaker signal, it is re-estimated and reconstructed again and subtracted from the baseband signal thereby removing the weaker signal from the stronger signal. This procedure is repeated continuously and finally we are able to obtain both the weak and strong signal at the detector output and we can use both the signals.

The main drawback with this system is that while sampling the received signal is it necessary that both the co-channel signals are in the same phase, they must not have any misalignment as it leads to degradation of the signal and increases the processing complexity.

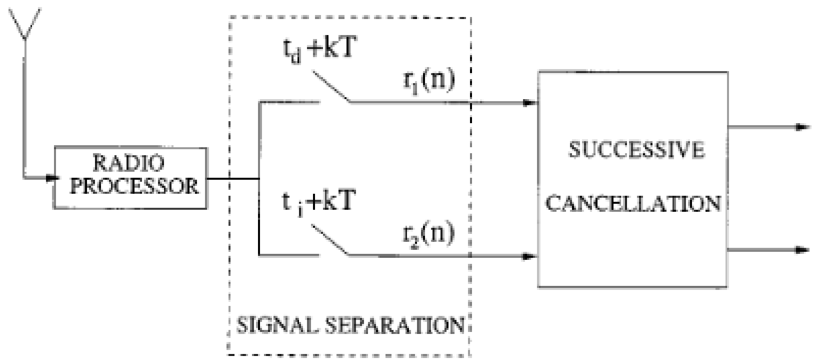

Fig 2. Successive cancellation using signal separation.

We can use the structure in Fig 2 to separate the signals of the co-channel by taking advantage of the time difference between the two signals. By employing two separate signal branches we are able to obtain the two different base band signals namely $r_1(n)$ and $r_2(n)$. As the incoming signal are all shifted in time due to phase difference between the $r_1(n)$ and $r_2(n)$. The first branch is designed with a sampling phase such that it is able to receive only the first co-channel signal thereby giving rise to the received signal $r_1(n)$. Similarly, the same applies to $r_2(n)$. Assuming the first branch gives us the desired output signal and the second branch is the interfering signal, we can represent the signals as

$$r_1(n) = c_d(n)a_d(n) + c_i(n)R_i(n) + z_1(n)$$
$$r_2(n) = c_i(n)a_i(n) + c_d(n)R_d(n) + z_2(n)$$

Where $z_1(n)$ and $z_2(n)$ are the uncorrelated noise samples. Each of the signals are demodulated and by using the procedure similar to the successive cancellation discussed in Fig. 1 the desired signals are processed and recovered. The reconstruction process is done using either hard or soft decision.

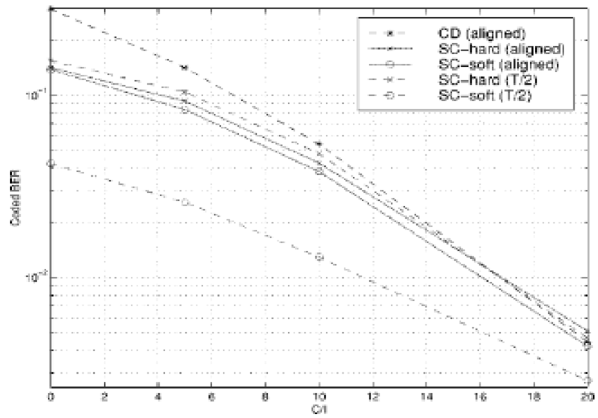

Fig. 3 Comparison of hard and soft decisions

Fig. 3 is the result of a simulation carried out on a TDMA system, using QPSK symbols. The entire simulation is carried out in a frequency non-selective Rayleigh fading channel. The detector uses a successive cancellation along with soft decision. It is evident that soft cancellation out-performs hard cancellation when employing successive cancellation, especially in the presence of a misalignment, the gains are very high.

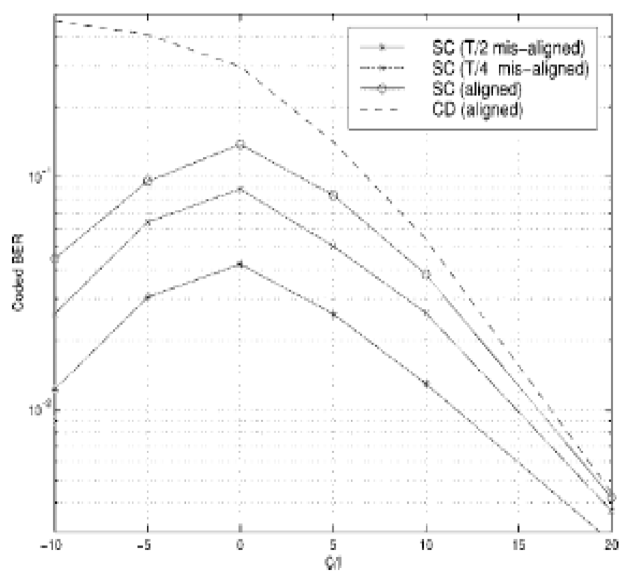

Fig. 4 Effect of misalignment on SC

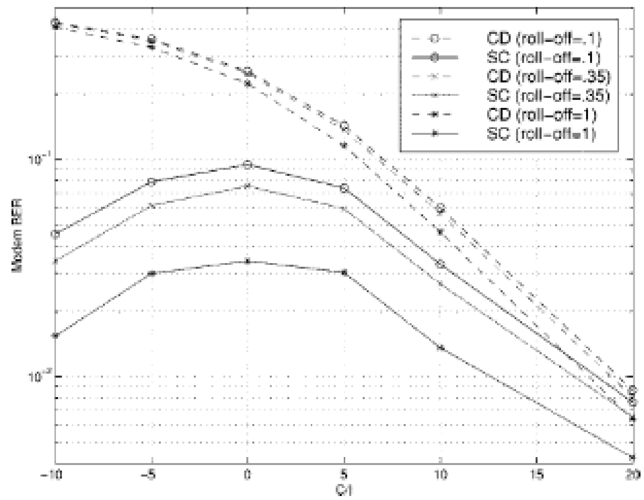

Fig. 5 Performance analysis

Fig. 4 provides the details regarding the effect of misalignment between the incoming signals on the soft cancellation. The analysis is carried out against the conventional demodulator (CD) used normally. It is seen from Fig. 4 that the performance of the SC is increased with increase in the misalignment of the signals. This is because the misalignment inherently helps in the process of separating the signals before the successive cancellation stage, thereby making further processing easier. This results in improved performance of the successive cancellation.

Fig. 5 provides details regarding the performance analysis of the system choosing a random signal misalignment. The SC provides better demodulation capability than the conventional Demodulator because the misalignment supports the working of the SC technique.

Minimum Mean Square Error (MMSE) Detector:

The other type of the detector which we will discuss is Minimum mean square error (MMSE) detector. The main task of detector is to determine which symbol was transmitted by the source. As the channel introduces the errors in the symbols sent from the source to the destination, this task of the detector becomes challenging. Also, as we have MIMO systems, many users can transmit data on the same shared channel and we have to do the estimation about the source. This can be done using the Minimum mean square error estimator. Minimum mean square estimation is the method of estimation which minimizes the mean square error.

Let us assume that the received symbol is Y and we want to estimate the value of Y i.e. $\hat{y}$.

Thus, in MMSE we minimize the mean square value of the error given by $E[(Y-\hat{y})^2]$. This value is calculated as:

$$E[(Y-\widehat{y})^2] = \int (y-\widehat{y})^2 f_Y(y)\, dy\ .$$

where, $f_Y(y)$ is the PDF (Probability distribution function) of Y.

Differentiating this equation, we get:

$$\int \hat{y} f_Y(y)\, dy = \int y f_Y(y)\, dy$$

Thus, we can write:

$$\hat{y} = E[Y]$$

This is the estimated value of Y.

Similarly, if we know a value x of any other symbol X, we can write the estimate of Y as:

$$E[\{Y - \hat{y}(x)\}^2 | X = x] = \int \{y - \hat{y}(x)\}^2 f_{Y|X}(y|x)\, dy$$

Where, $f_{Y|X}(y|x)$ is the conditional PDF of Y given we have the value of X.

Thus, we can write:

$$\hat{y}(x) = E[Y \mid X=x]$$

This can be used to determine which symbol was transmitted. For multiple values of X, we can write:

$$\hat{y}(x_1, x_2, x_3, x_4, \ldots x_n) = E[Y \mid X=x_1, X=x_2, X=x_3, X=x_4, \ldots X=x_n]$$

We can form a table for all the values of X and then compare the estimated value of X with the table to find out which symbol was transmitted.

This estimator is mostly used in OFDM (Orthogonal Frequency Division Multiplexing). This is more accurate than other type of estimators, but the calculation of Mean Square Error is complex.

Message Passing Algorithm (MPA):

Message passing algorithm is another decoding method used for estimating the symbols. There are many message passing algorithms which are being currently used. Two most extensively used MPAs are "Belief Propagation" (BP) and "Divide and Concur" (DC). Belief Propagation is iterative message passing algorithm whereas, Divide and Concur is a projection based algorithm. MPAs are used for estimation purposes, optimization, constraint satisfaction problems, etc. BP algorithms are very well known and used but, despite of having many important advantages over BP, it is not that known and used.

In estimation, we take as input some noisy measurement and try to infer from those measurements, the likely state of the hidden parts. In case of estimating which symbol was transmitted, we can have some received input which might contain some error. Then it can be removed using MPA and the correct codeword can be estimated. This codeword can either be the exact codeword which was transmitted or it can be most probable estimate of the codeword which was transmitted.

Factor Graphs:

The task of inferring the most probable state of a system is actually the optimization problem of finding the minimum energy of that system. Factor graph is the widely used graphical model for the estimation purpose using message passing algorithm. Factor graphs are bipartite graphs which contain two types of nodes: variable nodes and factor nodes.

The variable nodes are denoted using circles and they represent the variables in the optimization problem. A variable can take only a finite number of states. If a variable state is known ("observed"), we fill in the corresponding circle in the factor graph. If variable state of any node is not known ("hidden"), we use an open circle to denote such node.

The factor node in a factor graph represents how the overall objective function of our optimization problem breaks up into local terms. In each iteration, we update the costs of the factor node connected to each of the variable node using defined algorithm. Then a decision is made either "hard" or "soft", depending upon the necessity of the system. Fig. 6 represent a factor graph for the (N = 7, k = 4) Hamming code, which has seven codeword bits, of which the left-most four are information bits, and the last three are parity bits.

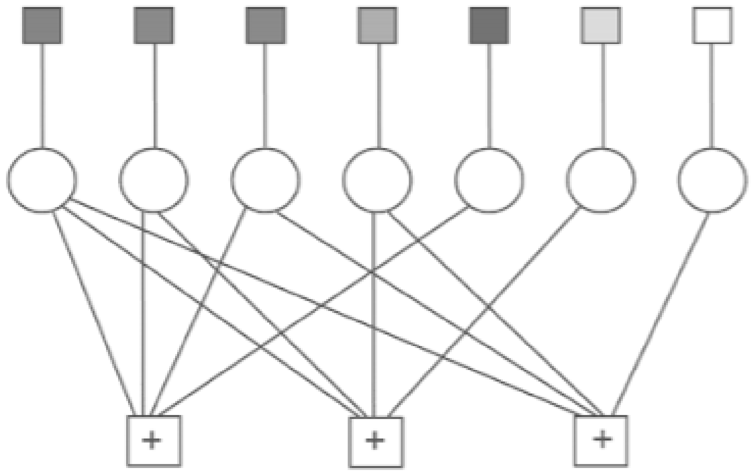

Fig. 6 A factor graph for the (N = 7, k = 4) Hamming code, which has seven codeword bits, of which the left-most four are information bits, and the last three are parity bits.

The whole algorithm is broken into five steps. Message passing algorithm got its name from the fact that in each step, messages are sent between nodes in the factor graph. In the first step, messages are initialized from variable node to the factor nodes. The initial messages are random messages, but we use non-informative messages from the hidden nodes and the messages that correspond to the observations from the observed nodes. Messages are thought as a variable telling its neighboring factors what it thinks its state is. In case of a non-informative message, the costs of each possible state is assigned to be equal.

In second state, the factor nodes compute messages that go back out to the neighboring hidden variable nodes. These messages are computed by taking into account what variable nodes have told them, the statistical relationships encoded by the factor node. The messages tell the neighboring nodes what state they should be in.

In third step, the hidden variable nodes inspect all the incoming messages and compute a "belief" about what their state should be. In BP algorithms, the belief takes the form of a cost, or a probability. In DC algorithms, the beliefs are just a single number, representing the current best guess for the state of that variable node.

Only BP algorithms have fourth step, while DC algorithms do not have this step. It involves thresholding the beliefs to obtain a single best guess for a variable node.

After fourth step is completed, we would have obtained a guess for the overall configuration of the factor graph, and we can use that guess to check for a termination condition. For example, in BP decoders of LDPC codes, we can check whether the guess is legal codeword that satisfies all the parity-check constraints. Or we can check whether the guess has changed from the previous iterations, or we have reached the maximum number of iterations. If we reach the termination condition, we can output the current guess or belief. Else, in the fifth step, the variable nodes will compute new messages to send back to the factor nodes, based on the messages they received and their beliefs. Then we go back to step two, and the cycle repeats.

Conclusion:

Through this work, we can infer the rudimentary working of the different decoders, each of which are unique and completely potential candidate for taking up the next generation of communication. On drawing a short comparison amongst the three decoding techniques, we can infer that SIC works better in an environment filled with co-channel and adjacent channel signals owing to its ability to eliminate the interference in the channel, but owing to its iterative procedure and constraints it will require many iterations to arrive at the final result. MMSE has the highest accuracy of the three but the algorithm is complex in comparison, therefore it will take up more processing duration in order to compute the results, whereas MPA algorithm is bit less complex than MMSE thereby providing faster computational capability at the expense of accuracy. Depending upon the system requirements, we can choose either MPA or MMSE decoder.

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