Kernels Introduction

1. Channel Coding

The Turbo codes we choose is a high-performance forward error correction code which is widely used in 3G/4G mobile communications. The rate of this turbo code is 1/3.

1.1 Turbo Encoder

The scheme of turbo code is a Parallel Concatenated Convolutional Code (PCCC) with two Finite State Machines (FSM) and one internal interleaver. The structure of turbo encoder is shown in Figure-1.

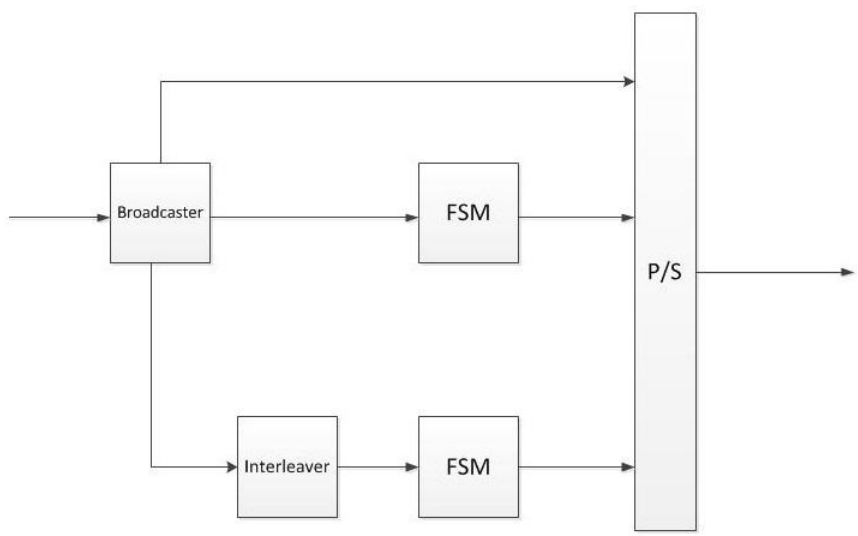

Figure-1 Turbo Encoder

The actual number of encoded bits is 3*K+T, where K is the number of input information bits and T is the number of termination bits. Termination bits that padded after the encoded bits will force two finite state machines back to zero state after encoding and will also help in decoding tails bits.

1.2 Turbo Decoder

The scheme of turbo decode includes two Soft-Input-Soft-Output (SISO) decoders and one internal interleaver/deinterleaver. The structure of turbo decoder is illustrated in Figure-2.

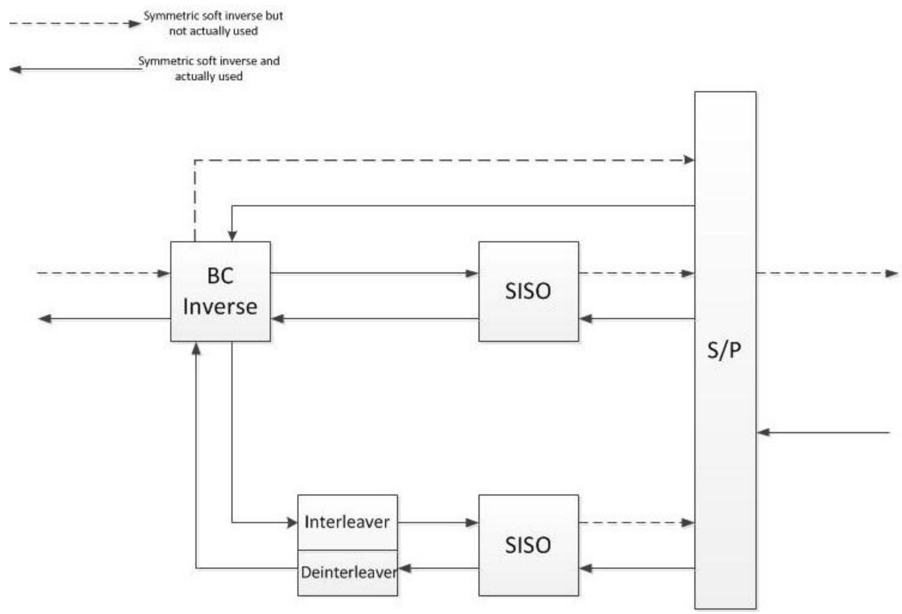

Figure-2 Turbo Decoder

Inside each SISO decoder, a forward and backward trellis traversal algorithm is performed. Turbo decoder works in an iterative fashion. By increasing iteration number in turbo decoder will both improve error correcting performance and increase the amount of computation.

2. Rate Match

The rate matcher contains a buffer and sub-block interleaver.

2.1 TxRateMatcher:

Perform subblock interleaver for each bit stream (i=0,1,2 since we apply Rate 1/3 Turbo Code) and then add redundant bits to form subframe.

2.2 RxRateMatcher:

Remove redundant bits for each bit stream and perform subblock deinterleaver.

3. Scramble/Descramble

The bit stream shall be scrambled with a User Equipment (UE) specified scrambling sequence in transmitter and this manipulation is reversed by a descrambler at the receiver side.

3.1 Scrambler:

Perform xor between encoded bit stream and UE specified scrambling sequence.

Descrambler:

Multiply real value soft information sequence and real value UE specified scrambling sequence (0->+1 1->-1).

4. Modulation/Demodulation

4.1 Constellation Mapper

The scrambled bits will be mapped into complex-valued constellation symbols. We include BPSK/QPSK/16QAM/64QAM in our benchmark.

4.2 Constellation Demapper

Constellation demapper generates soft information from noisy received data. We choose log-likelihood ratios (LLRs) as the soft information for each encoded bit that will be used by channel decoder as bit metrics. LLR for λ -th bit of symbol a conditioning on r is received and H is the channel effect is expressed as below.

$$\mathrm{LLR}\left(b^{\lambda}\middle|r,H\right)=log\frac{\Pr\{b^{\lambda}=0|\mathrm{r},\mathrm{H}\}}{\Pr\{b^{\lambda}=1|\mathrm{r},\mathrm{H}\}}\approx log\frac{\max_{\hat{a}\in\mathcal{A}_{\lambda}^{0}}p_r(r|\hat{a},H)}{\max_{\hat{a}\in\mathcal{A}_{\lambda}^{1}}p_r(r|\hat{a},H)}\approx\frac{1}{\sigma^2}(\min_{\hat{a}\in\mathcal{A}_{\lambda}^{0}}\|r-H\hat{a}\|-\min_{\hat{a}\in\mathcal{A}_{\lambda}^{1}}\|r-H\hat{a}\|)$$

$$\lambda=km-m,\ldots,km-1\;\;2^{m}ary\;constellation$$

$$\mathcal{A}_{\lambda}^{0}=\left\{a\colon b^{\lambda}=0\right\}\colon the\;subset\;of\;symbols\;a\;for\;which\;\lambda th\;bit\;equals\;0$$

$$\mathcal{A}_{\lambda}^{1}=\left\{a\colon b^{\lambda}=1\right\}\colon the\;subset\;of\;symbols\;a\;for\;which\;\lambda th\;bit\;equals\;1$$

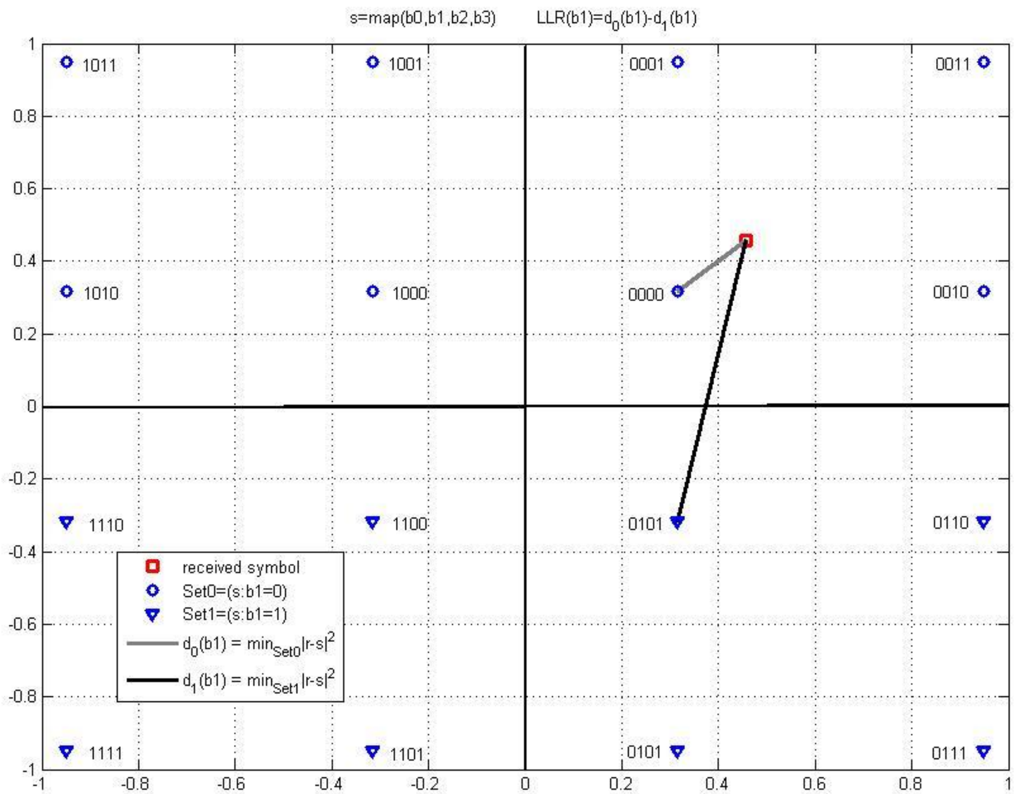

Figure-3 16QAM constellation and LLR(b1)

5. Multiple Input Multiple Output (MIMO)

MIMO is the use of multiple antennas at both the transmitter and receiver to catch either diversity gain or multiplexing gain.

5.1 MIMO for spatial multiplexing

MIMO for spatial multiplexing (SM) transmits independent data streams from each of the multiple transmit antennas. The benefit of SM is the increasing of data rate. This is the method we implemented in this benchmark.

The baseband model is: for subcarrier k $(k = 1,2,\dots,M)$

$$r^k_{N_r\times 1} = H^k_{N_r\times N_t} x^k_{N_t\times 1} + n^k_{N_t\times 1} \ .$$

$H^k_{N_r\times N_t}$ is the frequency domain channel matrix estimated from channel estimation block.

Nr: # of receiver antennas Nt: # of transmitter antennas

This is done in SubCarrier Mapper/Demapper kernel. Subcarrier mapper maps data symbols and insert reference signal into physical resources. If multiple users exist in the system, their data will be mapped into non-overlapping physical resources. Subcarrier demapper extract data and reference signal from physical resources for each user in the system.

5.2 MIMO for diversity

MIMO for diversity transmits a single data stream from each of the multiple transmit antenna. The single data stream is coded by space-time coding which improves the reliability of data transmission.

6. Fast Fourier Transform (FFT)

An FFT computes the Discrete Fourier Transform (DFT) in a faster way. An N-point DFT is defined by the formula. An FFT requires only $\theta(NlogN)$ operations to get the same result.

$X_k = \sum_{n=0}^{N-1} x_n e^{-i2\pi\frac{kn}{N}} \quad k = 0,1,\dots,N-1$

From the viewpoint of signal processing, FFT can convert time domain samples into frequency domain while IFFT does the reverse conversion. FFT is used by OFDM and SC-FDMA system. We implement SC-FDMA system since it is superset of OFDM system.

7. Channel Estimation

Channel State Information (CSI) can be estimated at the receiver side by Reference Signal (RS) in both time domain and frequency domain with various estimator such as Least Square (LS) estimator, Minimum Mean Square Error (MMSE) estimator. Compared to LS estimator, MMSE estimator provides better performance while it requires more computation and knowledge of channel. Moreover, estimation can also be done in both time domain and frequency domain.

Channel's frequency response LS estimation can be performed by a 1-tap equalization as:

$$\widetilde{H}_{LS}(k) = \frac{Y_P(k)}{X_P(k)} \quad k = 1,\dots,N.$$

Yp: received pilot signal Xp: pilot signal which is known to the receiver.

8. Equalizer

The receiver needs to remove the effect of channel by applying equalizer with the knowledge of CSI. Equalizer can also be done in either time domain or frequency domain.

The frequency domain LS equalizer is implemented by:

$$\widetilde{X(k)}_{data} = (\widetilde{H}(k)_{LS}{}^{H}\widetilde{H}(k)_{LS})^{-1}\widetilde{H}(k)_{LS}{}^{H}Y(k)_{data}$$

The frequency domain MMSE equalizer is implemented by:

$$\widetilde{X(k)}_{data} = (\widetilde{H}(k)_{LS}{}^{H}\widetilde{H}(k)_{LS} + \sigma^2 I)^{-1}\left(\widetilde{H}(k)_{LS}\right)^{H} Y(k)_{data}$$

$$\sigma: AWGN\ noise\ level$$

9. Channel

The channel kernel introduces both fading channel effects and additive white Gaussian noise into the system.

9.1 Fading channel

Except Gaussian Radom Channel (GRC), we adopt several channel models such as Extended Pedestrian A model (EPA), Extended Vehicular A model (EVA), Extended Typical Urban model (ETU), which provide more realistic channel scenario.

9.2 Additive White Gaussian Noise (AWGN)

AWGN is added at each receiver antennas with different level. The AWGN level is a useful information for some other kernels to improve performance such as demodulation, channel estimation, equalizer.

Application—LTE uplink system design and description

We built an application, 3GPP LTE uplink, using above kernels. The uplink system is organized as Figure-3. We implement the entire physical layer and the most computation intensive parts of transport layer—Turbo Codes and Rate Matcher. Different configurations affect the data rate, the configurations and corresponding peak data rate we supported is shown in table-1.

1. Turbo Encoder/Decoder

The FSM of Turbo Encoder in LTE is an 8-state recursive systematic convolutional encoder. The internal interleaver/de-interleaver adapt to 188 different input lengths from 40 to 6144. We set the iteration number of turbo decoder to be 5 considering the trade-off between performance and computation.

2. Single Carrier Frequency Diversity Multiple Access (SC-FDMA)

SC-FDMA is a precoded Orthogonal Frequency Diversity Multiplexing (OFDM) which has an additional transform precoding preceding the conventional OFDM processing. OFDM processing encodes data on multiple carrier frequencies. OFDM has a lot of advantages such as: high spectral efficiency, robust against several severe channel conditions without complex time-domain equalization, efficient implementation using FFT and so on. OFDM is applied in LTE Downlink (From Base Station to User Equipment) while SC-FDMA is realized in Uplink (From User Equipment to Base Station). Compared to OFDM, SC-FDMA has two main advantages which are critical to Uplink transmission: 1) SC-FDMA has a lower Peak-to-Average Power Ratio; 2) SC-FDMA is less sensitive to frequency offsets than OFDM.

In transmitter, we implement OFDM Modulation by performing IFFT and insert Cyclic Prefix (CP). In receiver, we eliminate the intersymbol interference by removing CP and convert data from time domain to frequency domain by FFT.

In SC-FDMA scheme, the transform precoder before conventional OFDM Modulation is done by an $2^a3^b5^c$ mixed radix FFT while the IFFT is performed in the transform decoder at the receiver side.

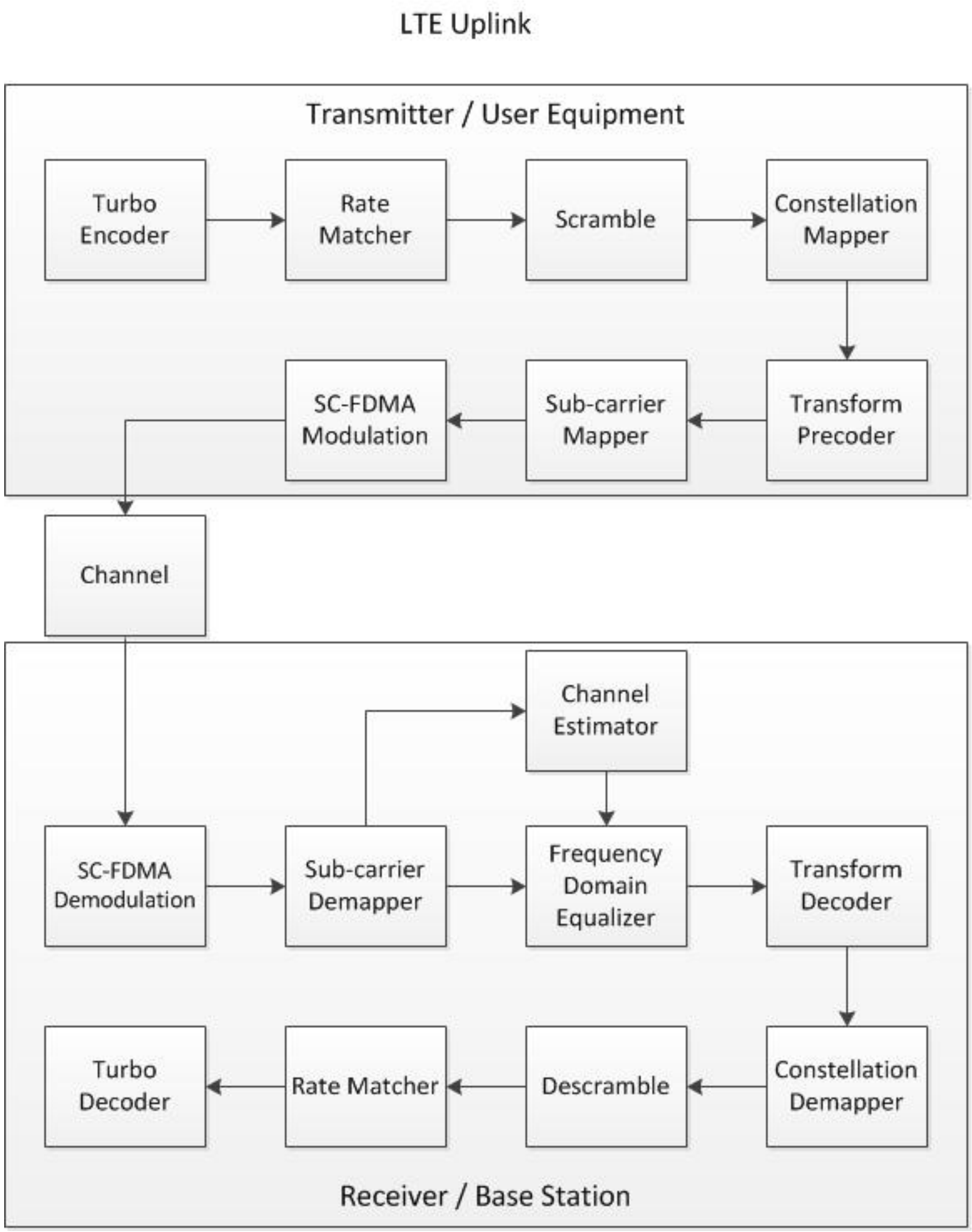

Figure -3 app: LTE Uplink

Transmission Bandwidth MHz	1.4		3		5		10		15		20	
FFT size Size of OFDM/SCFDMA size	128		256		512		1024		1536		2048	
Length of Cyclic Prefix (normal) in symbols	9		18		18		72		108		144	
FFT size=# of subcarrier	75		150		300		600		900		1200	
Antenna Configuration (Tx. Ant. –by- Rx. Ant.)	1x1	2x2	1x1	2x2	1x1	2x2	1x1	2x2	1x1	2x2	1x1	2x2
Constellation Scheme	QPSK											
Peak Data Rate(Mbps)		3.6	3.6	7.2	7.2	14.4	14.4	28.8	21.6	43.2	28.8	57.6
Constellation Scheme	16QAM											
Peak Data Rate(Mbps)	3.6	7.2	7.2	14.4	14.4	28.8	28.8	57.6	43.2	86.4	57.6	115.2
Constellation Scheme	64QAM											
Peak Data Rate(Mbps)	5.4	10.8	10.8	21.6	21.6	43.2	43.2	86.4	64.8	129.6	86.4	172.8

Table – 1 LTE uplink configuration and corresponding data rate

3. Channel Estimation

According to figure-4.left which illustrates the resource elements used for RS in LTE downlink transmission, a two dimension interpolation in both time and frequency domain is required. Figure-3.right interprets the location of RS in the LTE uplink transmission, only time domain interpolation should be applied. Unlike the downlink transmission, the uplink RS from different transmission antennas occupy the same physical resource elements. However, this RS is well designed such that they can be distinguished from each other at the receiver side. Channel estimator takes the received signal and known RS to estimate the CSI. CSI is used to compute the channel coefficients.

4. Equalizer

Taking advantage of OFDM/ SC-FDMA, channel equalization in LTE can be implemented simply by a Frequency Domain Equalizer (FDE) with the coefficients estimated by channel estimator.

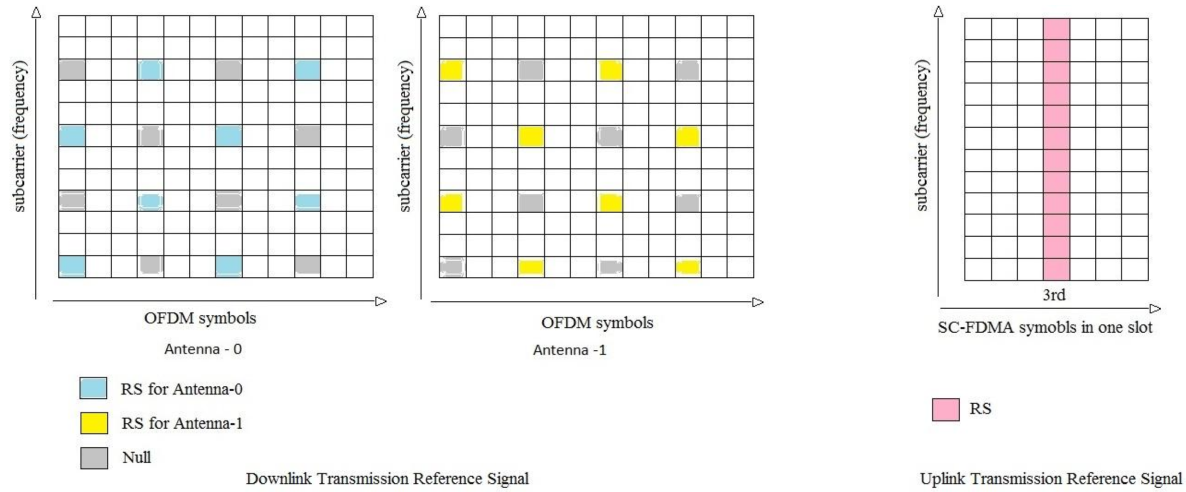

Figure -4 LTE Pilot signal allocation method