TMUX for 4G Mobile Communications

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Foreword

Various signal transmission methods are developed for the fourth generation (4G) mobile communication networks. They include WiMAX, OFCDM, Flash-OFDM and the next generation PHS. All those systems adopt OFDM for the signal transmission over non-line-of-sight (NLOS) propagation links. In this paper the Trans-multiplexer (TMUX) is proposed for 4G mobile communications. The TMUX includes OFDM as a special case; its generality allows more flexible design of the system.

The most difficult part of OFDM and OFCDM is the frame synchronization and removal of the guard time (GT) at the receiver in the deep interferences conditions among many different mobile terminals in operation in the same or adjacent cells.

The proposed TMUX system needs no frame synchronization at the receiver.

The FDM-CDMA system is particularly suitable for mobile communications as it combines both features of FDMA and CDMA. .

Contents

1. Propagation conditions in mobile communications

[1] Multi-path fading and delay spreads

In non-line-of-sight (NLOS) radio links multi-path fading is inevitable. The multi-path radio links cause fading in amplitude and spreading in propagation delays.

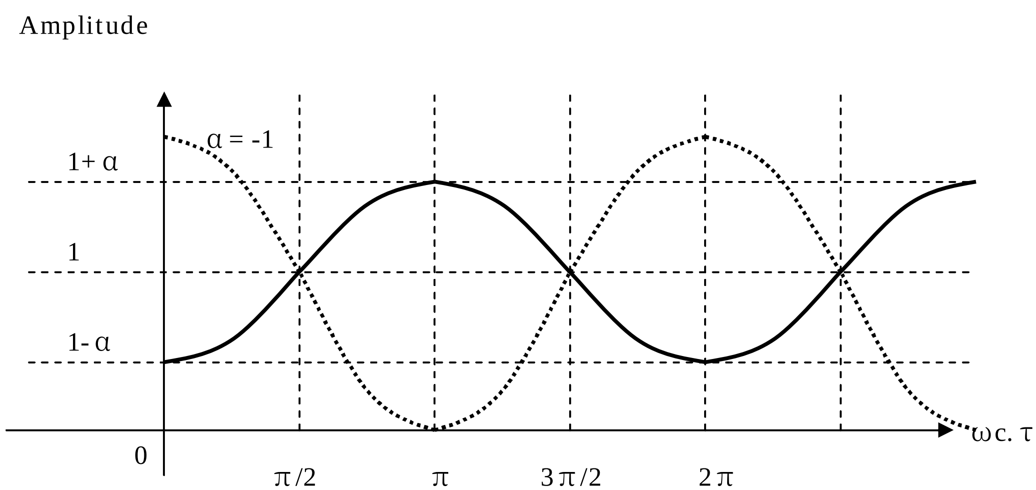
As the simplest case we examine a case that there is a main path and another path with relative amplitude α and delay τ.Let Eo the electric field of the direct path signal amplitude. Then the combined receive signal Er is given by;

$$Er = Eo\{ 1 + \alpha . e^{(-j\omega c. \tau)}\}$$

Where ωc is the angular frequency of the radio signal.

Then the transmission characteristics of the radio link will be as follows;

$$1 + \alpha .e^{(-j\omega c. \tau)} = \sqrt{[1+\alpha^2 - 2\alpha\cos(\omega c. \tau)]} .e^{[j.\arctan\{\alpha\sin(\omega c. \tau)/(1+\alpha\cos(\omega c. \tau))\}]}$$



Note the multi-path causes ripples in the transmission link frequency responses.

The transmission gain of the path is lost at certain frequency bands but then added at other bands. The OFDM and TMUX can take advantage of this feature for reliable signal transmission by combination of frequency diversity and forward error correction (FEC).

[2] Doppler spectrum spreads

Normally the mobile antenna is omni-directional and receives radio waves coming from all directions. As the mobile terminal moves at the velocity v, the radio waves from the front direction gets a positive Doppler effects and the signal frequency shifts to the higher side and the signals from the hind direction gets negative Doppler effects and the signal frequency gets to the lower side.

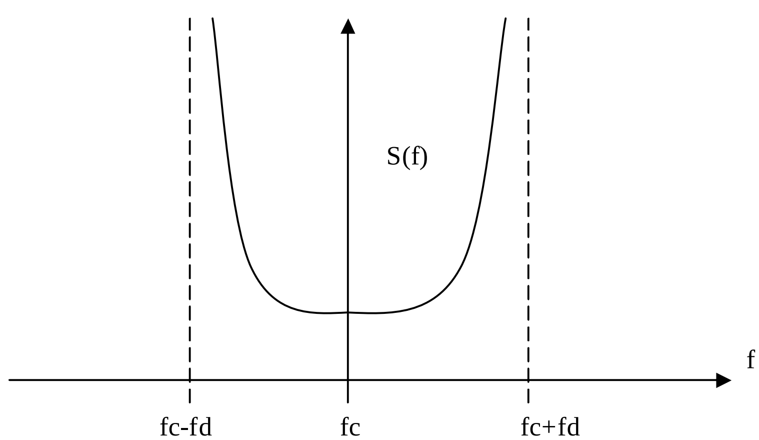
Suppose a sinusoidal signal is sent from the transmitter and the signal is received by a mobile moving at a speed v through the multi-path environments. Then it is observed that the single frequency spectrum signal received through the multi-path fading conditions is deformed due to the Doppler effects. The power spectrum of the receive signal spreads according to the following formula;

$$S(f) = bo/(\pi fd)/\sqrt{(1-\{(f-fc)/fd\}^2)}$$

Where bo is the receive signal power, fd is the Doppler frequency given by

$$fd = v/\lambda = fc.v/c$$

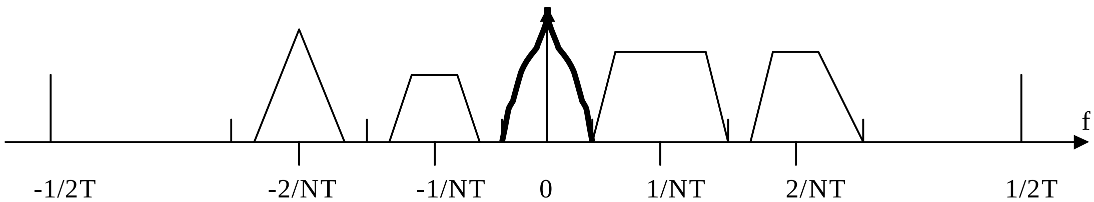
where fc is the carrier radio frequency, v the speed of the mobile and c the velocity of light. The shape of the carrier spectrum at the receiver is depicted in the following figure.



2. TMUX and FDM-CDMA systems

Historically the trans-multiplexer (TMUX) was developed for telephony networks where all signals were of the same bandwidth. The voice signals were bandwidth limited to 3.4(kHz, 3dB) and frequency multiplexed with $\Delta f = 4(\text{kHz})$ spacing.

The frequency spectrum of the conventional TMUX is depicted in the following figure.



The channel uniformity can simplify the structure of the trans-multiplexer.

2.1 TMUX multiplexer

Here we will design a TMUX that multiplexes N inputs at channel spacing Δf (Hz). The multiplexing frequency fs is given by;

$$fs = N.\ \Delta f$$

The channel filter G(z) is an FIR type that has response length of L samples.

Here L is chosen to a multiple of N as follows;

$$L = M.N$$

Then the channel filter is composed of sub-filters as follows;

$$G(z) = [l= 0,L-1]\sum\ g(l).z\char`^(-l)$$

$$= [i= 0, N-1]\sum\ z\char`^(-i).G[i](z\char`^N)$$

where the sub-filters are;

$$G[i](z\char`^N) = [l= 0, L/N-1]\sum\ g(\ l.N +i)z\char`^(-l.N) \qquad (i = 0,1,2,,,,,N-1)$$

The k-th signal X[k](z^N) (k= 0,1,2,,,,N-1) is filtered by G(z) to give

$$G(z).X[k](z\char`^N) = [i= 0, N-1]\sum\ z\char`^(-i).G[i](z\char`^N).X[k](z\char`^N)$$

The signal is then frequency converted to $k.\Delta f$, which is made by the variable conversion;

$$z = e\char`^(j2\pi fT) \rightarrow e\char`^(j2\pi(f- k.\Delta f),T) = W\char`^k\ .z$$

where $W = e\char`^(-j2\pi/N)$

$$G(z).X[k](z\char`^N)[\text{shifted at } k.\Delta f] = [i= 0, N-1]\sum\ (W\char`^k.z)\char`^(-i).G[i](z\char`^N).X[k](z\char`^N)$$

All the signals are now combined to give

$$SX(z) = [k=o,N-1]\sum G(z).X[k](z\char`^N)[\text{shifted at } k.\Delta f]$$

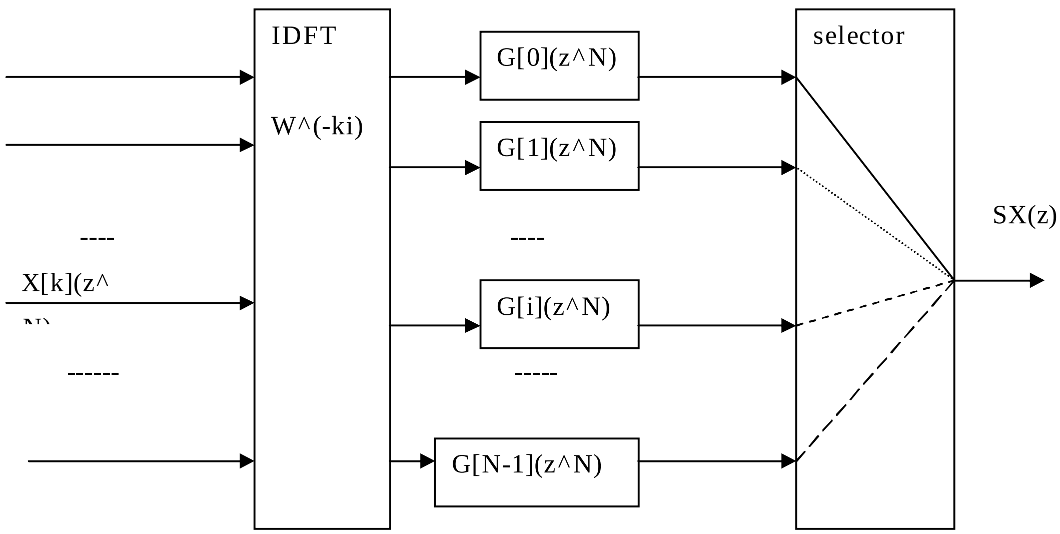
$$= [k=o,N-1]\sum[i= 0, N-1]\sum\ (W\char`^k.z)\char`^(-i).G[i](z\char`^N).X[k](z\char`^N)$$

$$= \sum[i= 0, N-1]\sum\ z\char`^(-i).G[i](z\char`^N).\ [k=o,N-1]\sum W\char`^(-k.i).X[k](z\char`^N)$$

= ∑[i= 0, N-1]∑ z^(-i).X(i)(z^N)

where X(i)(z^N) = G[i](z^N). [k=o,N-1]∑W^(-k.i).X[k](z^N) (i=0,1,2,,,,N-1)

The structure of the conventional TMUX is depicted in the following.



Structure of conventional TMUX multiplexer

2.2 TMUX de-multiplexer

The receive signal is sampled by the rate fs = 1/T.

Let us decompose the receive signal R(z) into N sub-sequences as follows;

R(z) = [n]∑r(n) .z^(-n)

= [m=0,N-1]∑z^(-m).R(m)(z^N)

where R(m)(z^N) = [n]∑z^(-n.N).r(n.N +m)

The receive channel filter H(z) is decomposed into sub-filters in the same manner as in the transmitter;

H(z) = [l= 0,L-1]∑ h(l).z^(-l)

= [i= 0, N-1]∑ z^(-i).H[i](z^N)

The filter tuned at k.Δf is given by

H[k](z) = [i= 0, N-1]∑ (W^k.z)^(-i).H[i](z^N)

The output of the filter H[k](z) is

H[k](z) . R(z) = [i= 0, N-1]∑ (W^k.z)^(-i).H[i](z^N) [m=0,N-1]∑z^(-m).R(m)(z^N)

= [i]∑[m]∑W^(-ki).z^{-(i+m)} H[i](z^N) .R(m)(z^N)

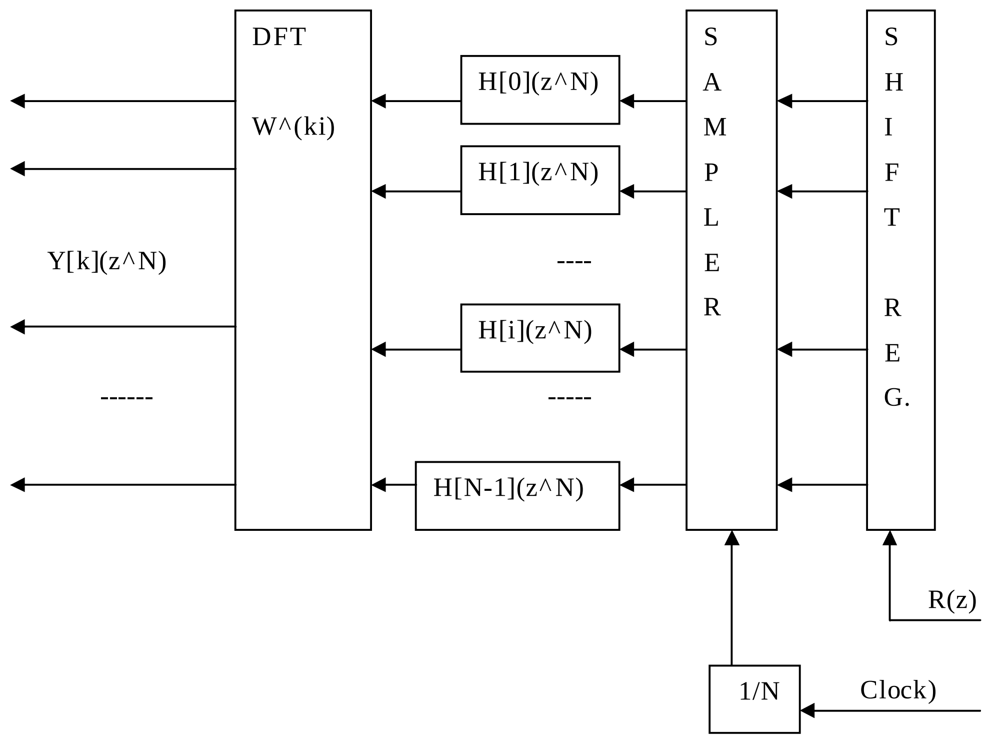
The signal is frequency converted from k.Δf→ 0 (Hz),which is done by the variable conversion z→W^(-k).z

The output Y[k](z) is given by;

$$Y[k](z) = [i]\sum[m]\sum W^{(k.m)}.z^{-(i+m)} H[i](z^N) .R(m)(z^N)$$

The bandwidth of Y[k](z) is frequency limited to Δf hence can be sampled at only Δf samples/sec. Here we select only i+m = N-1, which gives the output

$$Y[k](z^N) = z^{-(N-1)}. [m]\sum W^{(k.m)}. H[N-1-m](z^N) .R(m)(z^N)$$



Structure of conventional TMUX de-multiplexer

The mechanism of the frequency channels multiplexing and de-multiplexing is straight forward. If we let R(m)(Z^N) = X(m)(z^N) ,then

$$Y[k](z^N) = z^{-(N-1)}. [m]\sum W^{(k.m)}. H[N-1-m](z^N) .R(m)(z^N)$$

$$= z^{-(N-1)}. [m]\sum W^{(k.m)}. H[N-1-m](z^N).G[m](z^N). [k']\sum W^{(-k'.m)}.X[k'](z^N)$$

$$= z^{-(N-1)}.N. [m]\sum . H[N-1-m](z^N).G[m](z^N). X[k](z^N$$

$$+ z^{-(N-1)}. [m]\sum[k'=/=k]\sum W^{(k-k').m} .H[N-1-m](z^N).G[m](z^N). X[k'](z^N$$

The first term is the desired signal. The second terms are interferences from channels k' into channel k, which are suppressed by proper design of the channel filters G(z) and H(z).

2.3 FDM-CDMA

We send a signal X(z^N) through an interference limited radio link by FDM-CDMA

At the transmitter;

(1) Select a PN sequence c[k] (k=0,1,2,,,,N-1)

(2) Produce X[k](z^N) = c[k].X(Z^N)

(3) Put X[k](z^N) into TMUX multiplexer and transmit the multiplexed output

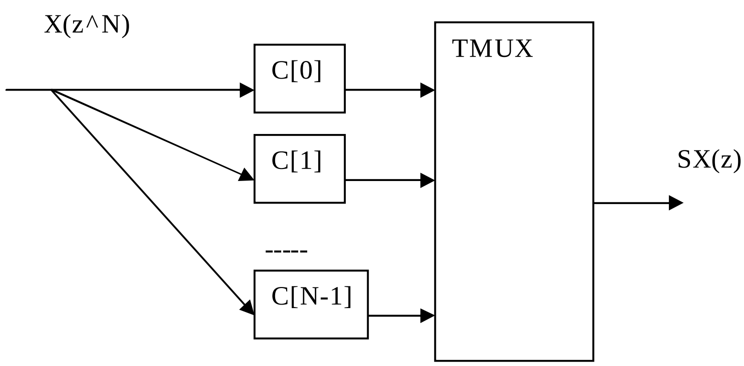
At the receiver; .

(4) Apply the receive signal into the TMUX de-multiplexer to get Y[k](z^N)

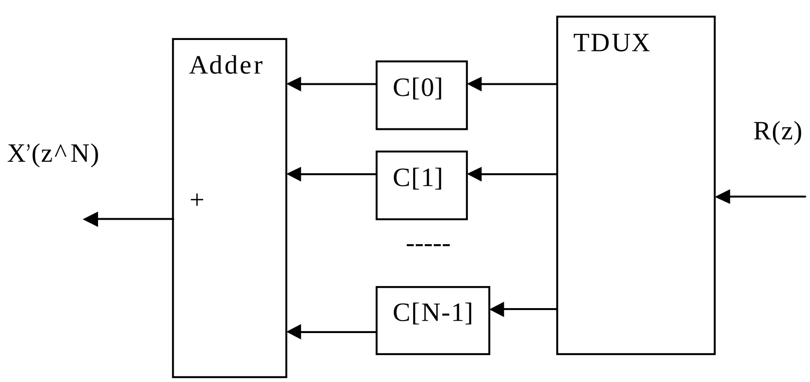
(5) Conduct the de-spreading by the following formula ;

Y(z^N) = [k=0,N-1] ∑ c[k].Y[k](z^N)

(6) The orthogonality of the PN sequences recovers the Y(z^N) = X(z^N)



FDM-CDMA Transmitter



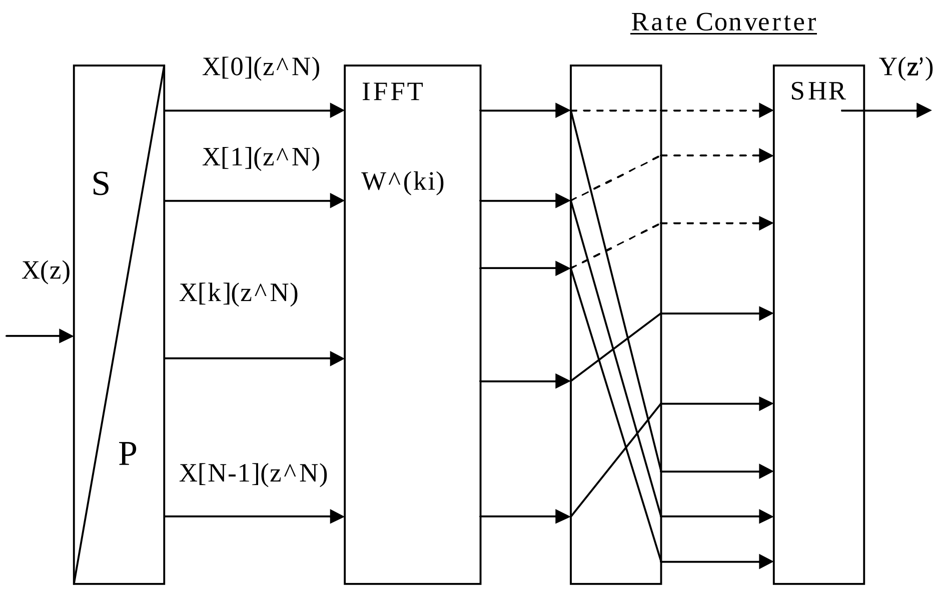
FDM-CDMA Receiver

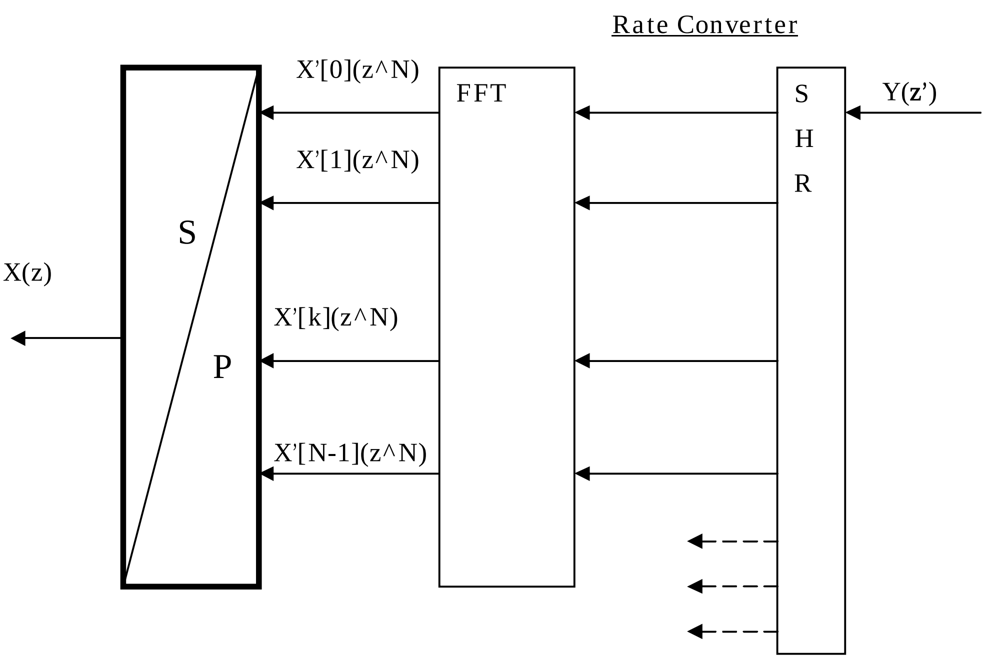
3 OFDM and OFCDM

OFDM (Orthogonal Frequency Division Multiplex) is widely used for digital broadcasting, mobile communication, wire-less LAN and ADSL systems.

The structures of the OFDM systems are depicted in the following figures.

3.1 Structure of OFDM network





Structure of OFGM transmitter and receiver

Rate conversion and GT insertion

A great feature of the OFDM is the insertion of the guard time (GT) to eliminate the multi-path interferences. The symbol rate is expanded at the transmitter and reduced at the receiver. The output Y(z') has then the sampling rate T' which is related with T by ; N.T = (N+G).T'. The transmit sampling frequency is 1/T' = (1 + G/N) /T, where G is the number of guard time samples. At the receiver the guard samples are discarded and N samples are fed to the FFT circuit.

3.2 Frequency spectrum of OFDM signal

The channel filter for OFDM is

$$G(z) = 1 + z^{-1} + \dots + z^{-(N-1)} = \{1 - z^{-N}\} / \{1 - z^{-1}\}$$

In frequency

$$G(j\omega) = e^{-j\omega T.(N-1)/2} . \sin(N\omega T/2) / \sin(\omega T/2)$$

The channel frequency characteristics extend beyond the channel bandwidth $\Delta f=1/NT$. In fact all channels signals overlap in the frequency domain. Thus the channels are not orthogonally multiplexed in the sense of the conventional TMUX.

However the total system with the transmitter and receiver combined gives orthogonal channels multiplexing. This is apparent from the IFFT and FFT operations at the TX and RX systems.

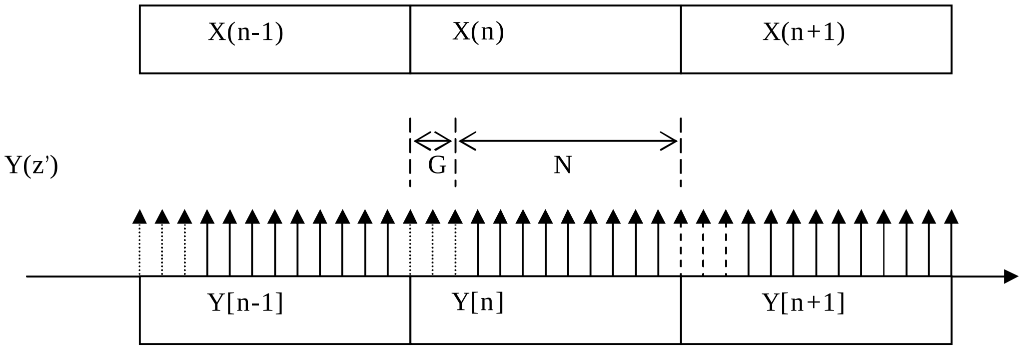
3.3 Elimination of multi-path fading by guard time

The OFDM is resilient against frequency selective fading since each channel is of very narrow bandwidth hence the fading can be treated as simple fluctuation of the signal amplitudes. The multi-path interferences occur in such a way that when certain channels are cancelled certain other channels are strengthened by phase summation of the direct path and multi-paths signals. Application of error correction coding together with interleaving can realize a reliable communication through such propagation paths.

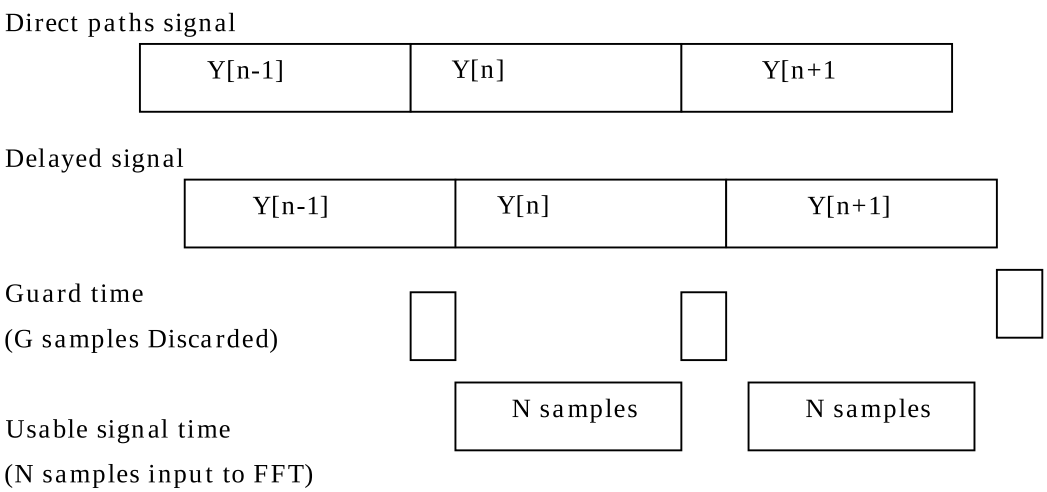
Another feature is the simple elimination of inter-symbol interferences caused by delay spreads through processing of the guard time. The duration of each channel data is NT. The earlier part of a receive signal can be the sum of the current data and the delayed tails of the previous data. This inter-symbol interference from earlier symbols can be eliminated by simply discarding the G samples appended in the rate conversion at the OFDM transmitter. If the guard time is greater than the delay spreads of the inter-symbols interferences, then the interferences can be effectively eliminated.

.The processing is depicted in the following figure.

Transmit signal



Receive signals



The guard time samples are discarded at the receiver to eliminate the inter-symbol interferences effectively. This is achieved at the cost of expanded RF bandwidth by the ratio; 1+ G / N. The guard time length is G.T' = G.T/(1+G/N) = (N.T).G/(N+G) which must be designed to be greater than the maximum multi-path delays in the system.

3.4 OFCDM

The OFDM and CDMA can be combined to form OCDM just as TMUX and CDMA are combined to form FDM-CDMA.

4. Comparison of OFDM/OFCDM and TMUX/FDM-CDMA

The essential differences are between OFDM and TMUX which are summarized in the following table.

Table 4-1 Comparison of OFDM and TMUX

	OFDM	TMUX
Channel filter response in time	u(t) – u(t-1/Δf) Rectangular function or Zero-th degree Holding	Nyquist filter Sin(2π.Δf.t)/ (2π.Δf.t) .F(t)
Channel filter response in frequency	Sin(2πf/Δf.)/ (2πf/Δf)	Nyquist filter
Signal bandwidth	Unlimited	Limited to Δf
Suppression of multi-path interferences	By Guard Time (GT) insertion and elimination	Selection of channel spacing so that 1/Δf >> Delay spreads and averaging by the channel filtering

Problems with OFDM

(1) Frequency Division Multiplex (FDM) is impossible with OFDM
Since OFDM is simply IFFT at the transmitter and FFT at the receiver, all the channels signals must be processed as a whole. No partial sharing of the channels among different users is impossible in theory. This problem is essential because of the overlapping Sin(2πf/Δf.)/ (2πf/Δf) type frequency spectrum of the OFDM signals.

(2) The receive frame synchronization and elimination of the GT portion of the signals becomes very difficult in mobile communications where many signals for different mobile terminals interfere heavily in the system.

Solutions by TMUX

The above problems can be solved by TMUX and FDM-CDMA.

(1) Since all channels in TMUX are separated in frequency they can be shared by different mobile terminals in FDM modes. Thus the FDM channel assignment can be applied to cellular systems on Δf channel units.

(2) The effect of the multi-path can be suppressed by setting 1/Δf >> delay spreads.
Further suppression can be achieved by the averaging function of the channel filters because the time length of the channel filters responses can be made significantly greater than 1/Δf. Remember L = M.N in Chapter 2.1.

(3) The FDM-CDMA can be effectively applied to mobile communications.

5. A design of a mobile communication system with TMUX/FDM-CDMA

Here we will design a mobile communication system which realizes a bandwidth greater than 10MHz, and the maximum cell size of 10km and allows the mobile terminals in motion at the speed up to v = 100 km per hour.

(1) Radio Frequency

fc = 2.5 (GHz)

(2) Maximum Doppler frequency

fd = fc .v/c = 2.5 x 10^9 x 100/3600 / (3x 10^8) = 231.5(Hz)

(3) Delay spreads τ

The absolute propagation time over 10km is 33 μs

Let us assume the delay spreads is about 10% of the absolute delay ; τ = 3 μs.

(4) Channel spacing Δf

It must satisfy fd << Δf << 1/ τ or 231.5 << Δf << 300(kHz)

A possible selection is Δf = 50(kHz)

(5) TMUX design

In order to achieve the bandwidth greater than 10 MHz, let us set N = 256.

The number of active channels will be 200, that gives the channel bandwidth 200.Δf = 10(MHz)

(6) The channel filter

The Nyquist type filter with roll-off factor 0.25.

The number of taps in the channel filter; L = M.N = 10 x 256 = 2560.

The time response length ; L/(NΔf) = 200 (μs) >> τ (3.3 μs)

(7) Maximum Data rate for QPSK modulation

2 x 200Δf / 1.25 = 16(Mbps)

6. Conclusion

The OFDM and OFCDM have difficulties to apply to the next generation mobile communication because of the fundamental nature of the OFDM. Another practical difficulty is in the receive frame synchronization and removal of the GT portion of the signals under heavy interference radio links among many mobile terminals.

The TMUX can provide independent frequency channels, hence can be applied to FDM operation for the mobile networks. The FDM-CDMA combines the FDM by TMUX and CDMA applied on the frequency domain. The FDM- CDMA can achieve an instant de-spreading function which is superior to the conventional CDMA on the time domain. The FDM-CDMA is effective to achieve reliable communications under heavy interference conditions and also simplifies the communication controls such as hand-over operations.

References

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