

Adaptive Frequency Hopped Alamouti-Coded OFDM System

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- In modern wireless communications, power and bandwidth are two of the most important resources
- Recent demand is for high data rate and to support more number of users
- In real scenario, the performance may degrade because of fading nature of the Rayleigh multipath channel
- For a power and bandwidth limited system, diversity can be used to enhance the system performance

Diversity

- Diversity order measures the number of available independent copies of the same signal
- The diversity gain is achieved using one of the following diversity scheme:
 - Frequency Diversity
 - Time Diversity
 - Space Diversity
- Transmit diversity is a class of Space diversity, where multiple antennas are used at the transmitter

OFDM

- Multichannel transmission scheme through which very high data transmission rate can be achieved
- Transmitting sub-carriers used are orthogonal to each other
- Sub-carriers of an OFDM can be represented as

$$\{e^{j2\pi f_k t}\}_{k=0}^{N-1}$$

$$f_k = \frac{k}{T_{sym}} \text{ where, } 0 \leq k \leq N-1$$

- OFDM decomposes a wideband frequency-selective channel into several parallel narrowband frequency flat-fading channels

- Thus, avoids the problem of inter-symbol interference (ISI) in frequency selective channels
- The discrete-time baseband model of an OFDM signal can be represented by:

$$y[m] = \sum_{l=0}^{L-1} h_l x[m-l] + w[m] \quad (1)$$

- Where, L is the number of taps of the Rayleigh channel model, w is the AWGN (Additive White Gaussian Noise) and h_l is the l_{th} tap of the Rayleigh channel. The channel h is normally distributed $h \sim N(0, 1)$

System Model

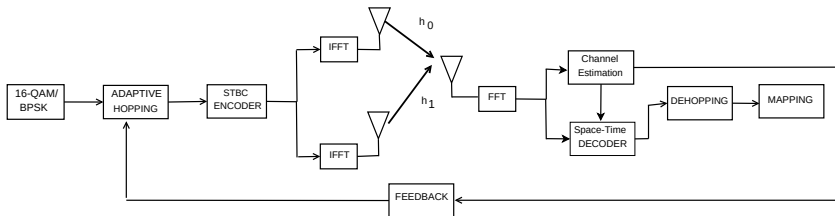


Figure: AFH Alamouti-Coded OFDM System

Modulation Mode	BPSK	16QAM
Number of Bits per Symbol	1	4
FFT Points	64	128
Number of Sub-carriers	64	128
Length of CP	16	16
Number of Data Sub-carriers	52	112
Channel Model	AWGN and Rayleigh	AWGN and Rayleigh
Channel Taps	10	10

Table: Simulation Parameters

- Assumptions:
 - Single User transmission case
 - Channel State Information (CSI) known at the receiver
 - Slow fading channel
 - Some feedback mechanism exist between receiver and transmitter

Frequency Hopping

- Exploits the frequency diversity
- Provides low probability of interception
- Hopping pattern generated is random
- Types of Frequency Hopping
 - RF-Carrier Frequency Hopping
 - Sub-carrier Hopping

Types of Sub-carrier Hopping

- Uniform Frequency Hopping
- Non-Uniform Frequency Hopping
- Adaptive Frequency Hopping

Uniform Frequency Hopping

- For each OFDM symbols, equal translation of all the sub-carriers across the band is provided

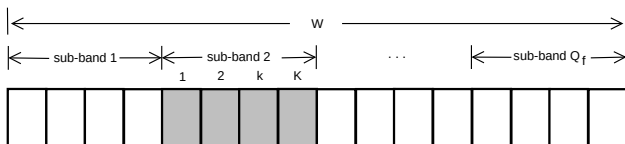
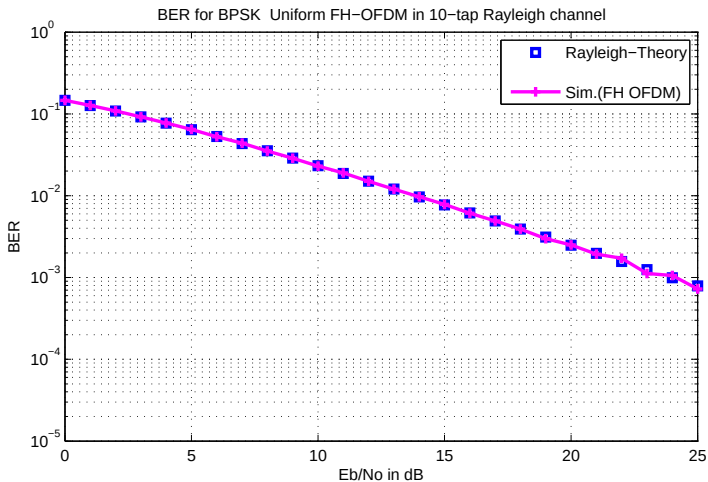


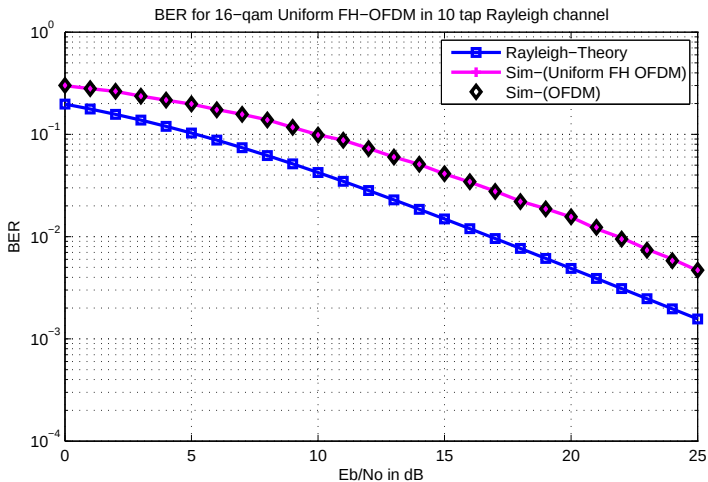
Figure: Uniform Sub-carrier Hopping

- Bandwidth W is partitioned into number of sub-bands, indexed from $q = 1, 2, \dots, Q_f$ and each of the sub-bands has K sub-carriers
- Where, $Q_c = K \cdot Q_f$ is the total number of sub-carriers
- A single user can select any K number of sub-carriers from the Q_c available sub-carriers

Result for Uniform Frequency Hopping for BPSK OFDM



Result for Uniform Frequency Hopping for 16-QAM OFDM



Non-Uniform Frequency Hopping

- For each OFDM symbols, different translation for each of the sub-carriers of the same user across the band is provided

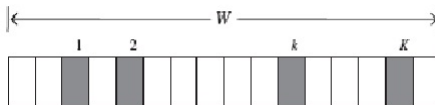
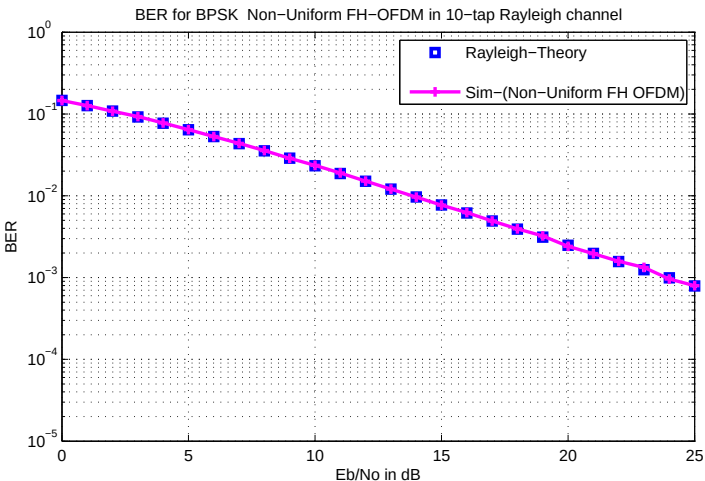


Figure: Non-Uniform Sub-carrier Hopping

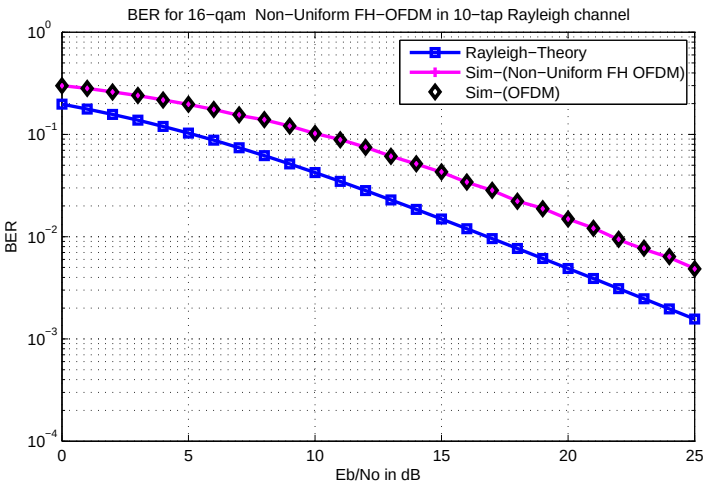
- User can use any of the K among the Q_c available sub-carriers
- Sub-carriers occupied by a user may not be adjacent to each other
- Advantage of this hopping pattern is that it reduces the ICI (Inter-Carrier Interference)

* M. Jiang and L. Hanzo, "Multiuser mimo-ofdm systems using subcarrier hopping," Communications, IEE Proceedings-, vol. 153, no. 6, pp. 802-809, 2006

Result for Non-Uniform Frequency Hopping for BPSK OFDM



Result for Non-Uniform Frequency Hopping for 16-QAM OFDM

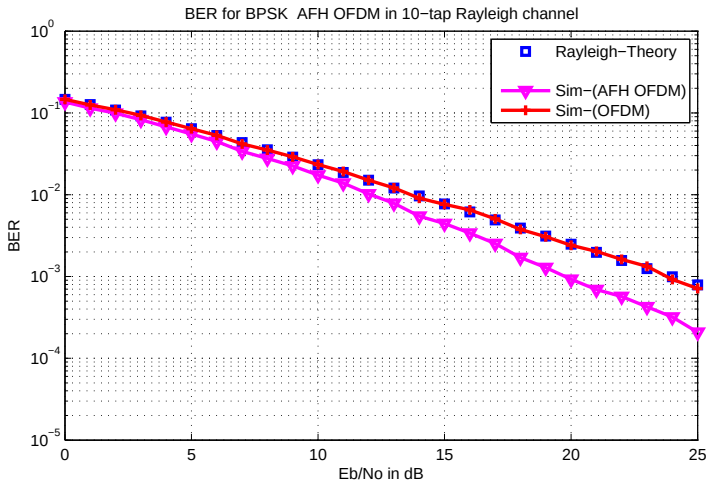


Adaptive Frequency Hopping

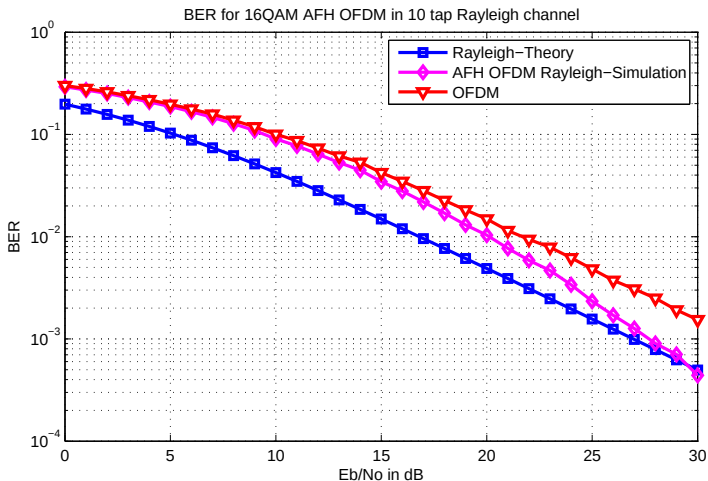
- Hopping pattern is decided based on the channel conditions
- LQA (Link Quality Analyser)** is used at the receiver to find the SNR (Signal to Noise Ratio) for each sub-carrier
- Feedback channel informs about the channel conditions back to the transmitter
- Sub-carriers having the best SNR are selected for transmission
- Channel assumed to remain constant for l (4 to 10) OFDM symbol periods

**F. Wang and X. He," The Performance Analysis of AFH-OFDM System Based on Simulink," in (WiCOM), 2011, 7th International Conference

Result for Adaptive Frequency Hopping for BPSK OFDM



Result for Adaptive Frequency Hopping for 16-QAM OFDM



Channel Estimation

- OFDM symbols get distorted due to channel conditions and presence of noise
- For correct detection of data, channel should be estimated and compensated
- Channel estimation is done using pilot-symbols
- Channel across each sub-carrier can be independently estimated for OFDM symbols

Pilot Arrangement

- Pilot-aided estimation can be of three types
 - Block-Type Pilot Arrangement
 - Comb-Type Pilot Arrangement
 - Lattice-Type Pilot Arrangement

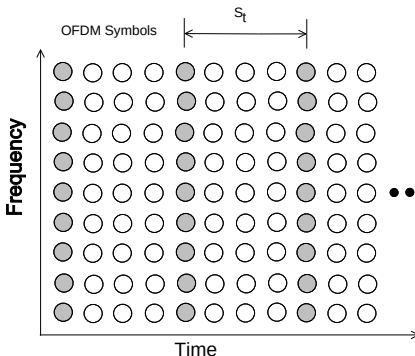
Block-Type

- Pilots at all sub-carriers are transmitted periodically
- To mitigate the effects of time-varying channel, pilot symbols should be placed in respect to the coherence time
- This type of pilot-arrangement is applicable for slow-varying channels
- Each channel can be estimated independently as they are orthogonal (free from ISI) to each other
- The pilot symbol period must satisfy the inequality:

$$S_t \leq \frac{1}{f_D}$$

- Where, S_t is the pilot symbol period

- Pilot arrangement for a Block-type*



- Where, f_D is the doppler frequency given by:

$$f_D = \frac{v}{c} * f_c * \cos \theta$$

*S. Coleri, M. Ergen, A. Puri, and A. Bahai, "Channel estimation techniques based on pilot arrangement in ofdm systems," Broadcasting, IEEE Transactions on, vol. 48, no. 3, pp. 223-229, 2002

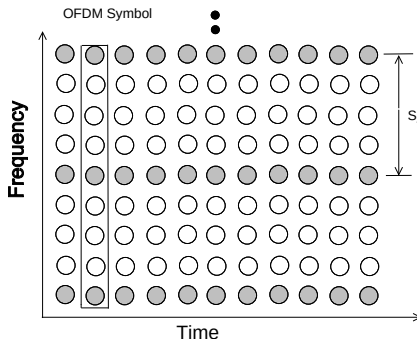
Comb-Type

- Pilot tones are equally spaced apart in each of the OFDM symbol
- To mitigate the effects of frequency-selective channel, pilot symbols should be spaced apart as the coherent bandwidth
- This type of pilot-arrangement is applicable for fast varying channels
- Channel estimated at the pilot sub-carrier is used to interpolate the rest of the channels
- The frequency spacing for pilot symbols must satisfy the inequality:

$$S_f \leq \frac{1}{\sigma_{max}}$$

- Where, S_f is the pilot symbol spacing

- Pilot arrangement for a Comb-type*



- Where, σ_{max} is the maximum delay spread, incurred due to multipath

*S. Coleri, M. Ergen, A. Puri, and A. Bahai, "Channel estimation techniques based on pilot arrangement in ofdm systems," Broadcasting, IEEE Transactions on, vol. 48, no. 3, pp. 223-229, 2002

Channel Interpolation

- Channel information at pilot sub-carriers are used to estimate channels at data sub-carriers through interpolation
- Channel estimation using linear interpolation at data-carrier k , $mL < k < (m+1)L$, is given by:

$$\begin{aligned}
 H_e(k) &= H_e(mL + l); & 0 \leq l < L \\
 &= (H_p(m+1) - H_p(m)) \frac{l}{L} + H_p(m) & (2)
 \end{aligned}$$

- Estimate of channel using second order interpolation is given by:

$$\begin{aligned} H_e(k) &= H_e(mL + l) \\ &= c_1 H_p(m-1) + c_0 H_p(m) + c_{-1} H_p(m-1) \end{aligned} \quad (3)$$

- Where,

$$\begin{cases} c_1 = \frac{\alpha(\alpha-1)}{2} \\ c_0 = -(\alpha-1)(\alpha+1); \alpha = \frac{l}{N} \\ c_{-1} = \frac{\alpha(\alpha+1)}{2} \end{cases}$$

- Performance of second order interpolation is better than the linear interpolation
- To attain higher accuracy for estimation, higher order interpolation can be used
- Computational complexity increases proportionally with the order of interpolation

Lattice-Type

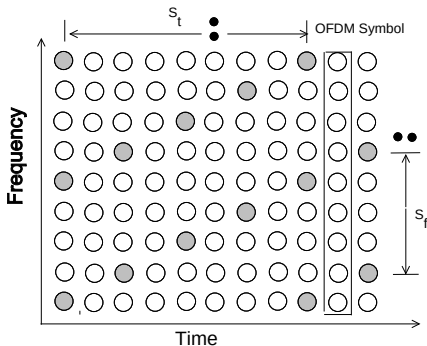
- Pilot tones are spaced apart equally along the frequency and time axis
- Pilot tones spaced in both frequency and time axis are used for interpolation and for channel estimation
- To mitigate the effects of frequency-variations and time-variation of channel, the arrangement of pilot symbols must satisfy the below inequalities

$$S_f \leq \frac{1}{\sigma_{max}}$$

and

$$S_t \leq \frac{1}{f_D}$$

- Pilot arrangement for a Lattice-type



- Where, S_t is the pilot symbol period and S_f is the pilot symbol spacing
- Where, σ_{max} is the maximum delay spread, incurred due to multipath and f_D is the doppler frequency

Channel Estimation Techniques

- Channel estimation based on training symbols provides good performance
- Efficiency of transmission decreases because of the addition of overhead training symbols
- Techniques used for channel estimation are:
 - LS (Least Square)
 - MMSE (Minimum Mean Square Error)

- The diagonal matrix for N sub-carriers for the training symbols can be represented as:

$$X = \begin{bmatrix} X[0] & 0 & \cdots & 0 \\ 0 & X[1] & \cdots & 0 \\ \vdots & & \ddots & \\ 0 & \cdots & 0 & X[N-1] \end{bmatrix}$$

- Where $X[K]$ represents the pilot tone present at the K th sub-carrier
- For each sub-carrier k , the received training signal can be represented as

$$Y[k] = H[k]X[k] + z[k]; \quad K = 0, 1, \dots, N-1$$

- $H(k)$ is the channel vector and $Z(k)$ is the noise vector, with $E\{Z[K]\} = 0$ and $Var\{Z[K]\} = \sigma_z^2$

LS Channel Estimation

- Let channel estimate of H be denoted as $\hat{H}$
- Least-square estimation is used to minimize below cost function

$$J(\hat{H}) = \|Y - X\hat{H}\|^2$$

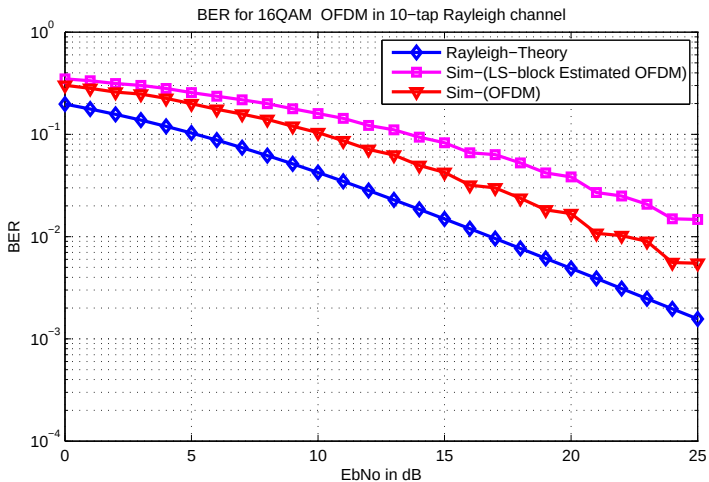
- The LS estimate of channel is:

$$\hat{H}_{LS} = X^{-1}Y$$

- For ICI-free condition

$$\hat{H}_{LS}[k] = \frac{Y[k]}{X[k]}; \quad k = 0, 1, \dots, N-1$$

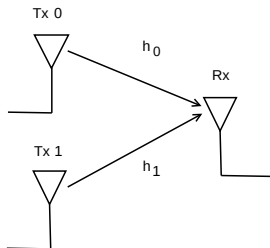
Result for LS Block Estimated for 16-QAM OFDM



- Alamouti is a class of STBC (Space-Time Block Code)
- L transmit antennas present at the transmitter can provide diversity order of L
- Simplest and most elegant scheme for achieving transmit diversity by utilizing the degree of freedom*

*S. Alamouti, 'A simple transmit diversity technique for wireless communications,' Selected Areas in Communications, IEEE Journal on, vol. 16, no. 8, pp. 1451-1458, 1998

Alamouti Scheme



- Achieves the same diversity order as MRRC (Maximal-Ratio Receiver Combining) with one transmit antenna and two receive antennas
- This scheme can be generalised to two transmit antenna and M receive antennas*

*Z. Jie, L. Liang, and L. Jin, "Performance analysis of space time block code in mimo ofdm systems," in Communication Software and Networks (ICCSN), 2011 IEEE 3rd International Conference on, 2011, pp. 13-16

The Encoding and Transmission Scheme

	antenna 0	antenna 1
time t	s_0	s_1
time $t+T$	$-s_1^*$	s_0^*

Table: Encoding and Transmission Scheme

- If T is considered as symbol duration then the received signal y_0 and y_1 at time t and $t + T$ is given by

$$y_0 = y(t) = h_0 s_0 + h_1 s_1 + w_0 \quad (4)$$

$$y_1 = y(t + T) = -h_0 s_1^* + h_1 s_0^* + w_1 \quad (5)$$

- The above equation can be written as :

$$\begin{bmatrix} y_0 & y_1 \end{bmatrix} = \begin{bmatrix} h_0 & h_1 \end{bmatrix} \begin{bmatrix} s_0 & -s_1^* \\ s_1 & s_0^* \end{bmatrix} + \begin{bmatrix} w_0 & w_1 \end{bmatrix} \quad (6)$$

- Since, we are interested in detecting s_0 and s_1 . So, the above equation can be rewritten as:

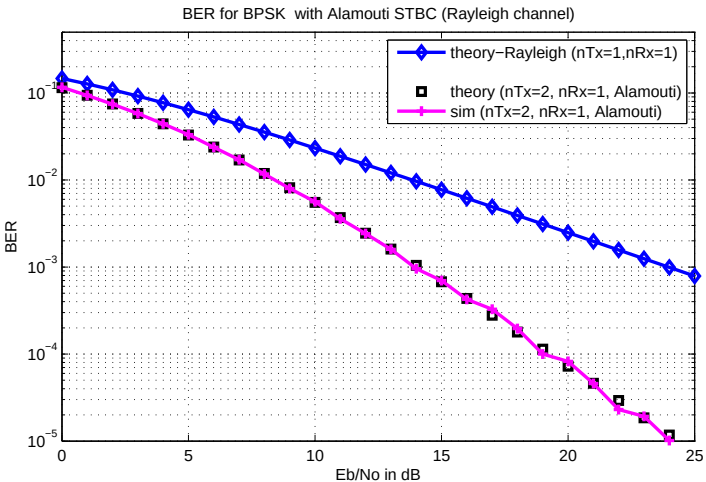
$$\begin{bmatrix} y_0 \\ y_1^* \end{bmatrix} = \begin{bmatrix} h_0 & h_1 \\ h_1^* & -h_0^* \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \end{bmatrix} + \begin{bmatrix} w_0 \\ w_1^* \end{bmatrix} \quad (7)$$

- The square matrix of above equation has it's columns orthogonal
- Hence, the detection problem for s_0 and s_1 can be decomposed to

$$\tilde{s}_0 = h_0^* y_0 + h_1 y_1^* \quad (8)$$

$$\tilde{s}_1 = h_1^* y_0 - h_0 y_1^* \quad (9)$$

Result for Alamouti-Coded BPSK



Alamouti Coded OFDM System

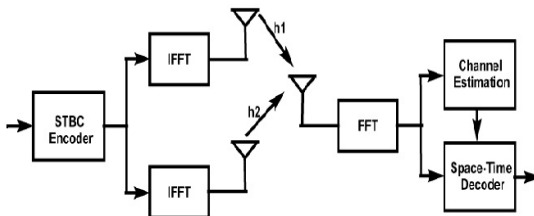


Figure: Alamouti Coded OFDM system

- Data are multiplexed into two streams s_0 and s_1
- Underlying concept of transmission is same as in Alamouti system*

*J. Kim, R. Heath, and E. Powers, "Receiver designs for alamouti coded ofdm systems in fast fading channels," Wireless Communications, IEEE Transactions on, vol. 4, no. 2, pp. 550-559, 2005

Frequency Domain Analysis

- The symbol s_0 is given by

$$s_0 = X_1(k) = [X_1(0), X_1(1), \dots, X_1(N-1)]$$

and s_1 is given by

$$s_1 = X_2(k) = [X_2(0), X_2(1), \dots, X_2(N-1)]$$

- Let, Y_1^1 and Y_1^2 represents the output of first antenna at time t and time $t + T$
- Similarly, Y_2^1 and Y_2^2 represents the output of second antenna at time t and time $t + T$

- The output from the two antennas at time t can be written as:

$$Y_1^1(k) = H_1(k)X_1(k) + W_1(k) ; k = 0, 1, \dots, N - 1$$

$$Y_2^1(k) = H_2(k)X_2(k) + W_1(k) ; k = 0, 1, \dots, N - 1$$

- Similarly, the symbols transmitted at time $t + T$ by the two antennas is given by

$$s_3 = -X_2^* = [-X_2^*(0), -X_2^*(1), \dots, -X_2^*(N - 1)]$$

and that transmitted by antenna 2 is

$$s_4 = X_1^* = [X_1^*(0), X_1^*(1), \dots, X_1^*(N - 1)]$$

- The output of the two antennas at time instant $t + T$ can be written as:

$$Y_1^2(k) = -H_1(k)X_2^*(k) + W_2(k) ; k = 0, 1, \dots, N - 1$$

$$Y_2^2(k) = H_2(k)X_1^*(k) + W_2(k) ; k = 0, 1, \dots, N - 1$$

- Hence, the received symbols Y_1 and Y_2 is given by the sum of the two transmitted symbols by the two antennas at time t and $t + T$

$$Y_1(k) = H_1(k)X_1(k) + H_2(k)X_2(k) + W_1(k)$$

$$Y_2(k) = -H_1(k)X_2^*(k) + H_2(k)X_1^*(k) + W_2(k)$$

$$k = 0, 1, \dots, N - 1$$

- For decoding purpose we take the conjugate of $Y_2(k)$ to get

$$Y_2^*(k) = -H_1^*(k)X_2(k) + H_2^*(k)X_1(k) + W_2^*(k)$$

$$k = 0, 1, \dots, N - 1$$

Equation for $Y_1(k)$ and $Y_2^*(k)$ can be combined and can be written as

$$Y(k) = A(k)X(k) + W(k) \quad (10)$$

- Where,

$$Y(k) = \begin{bmatrix} Y_1(k) \\ Y_2^*(k) \end{bmatrix}, \quad A(k) = \begin{bmatrix} H_1(k) & H_2(k) \\ H_2^*(k) & -H_1^*(k) \end{bmatrix}$$

$$X(k) = \begin{bmatrix} X_1(k) \\ X_2(k) \end{bmatrix}, \quad W(k) = \begin{bmatrix} W_1(k) \\ W_2^*(k) \end{bmatrix}$$

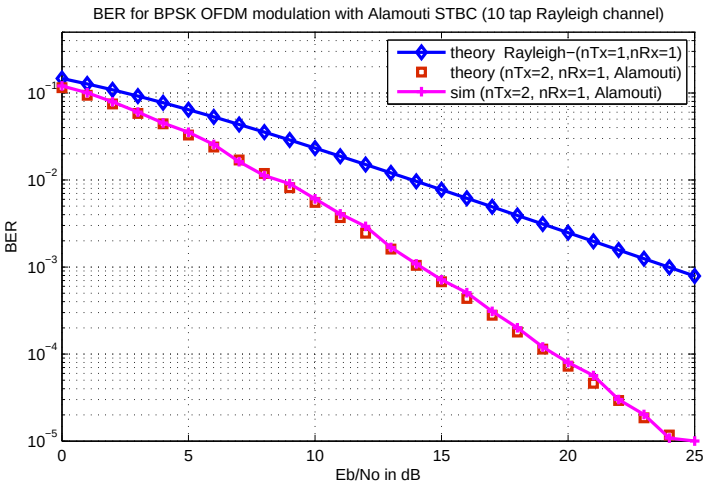
- The symbols at the receiver can be detected by multiplying $Y(k)$ with $A^H(k)$ and can be represented as

$$\hat{X}(k) = A^H(k)Y(k)$$

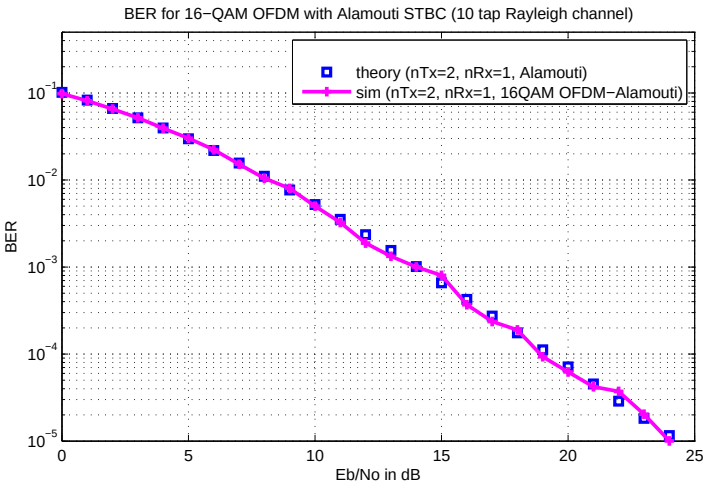
- Where,

$$\hat{X}(k) = \begin{bmatrix} \hat{X}_1(k) \\ \hat{X}_2(k) \end{bmatrix}, \quad A^H(k) = \begin{bmatrix} H_1^*(k) & H_2(k) \\ H_2^*(k) & -H_1(k) \end{bmatrix}$$

Result for OFDM Alamouti-Coded BPSK



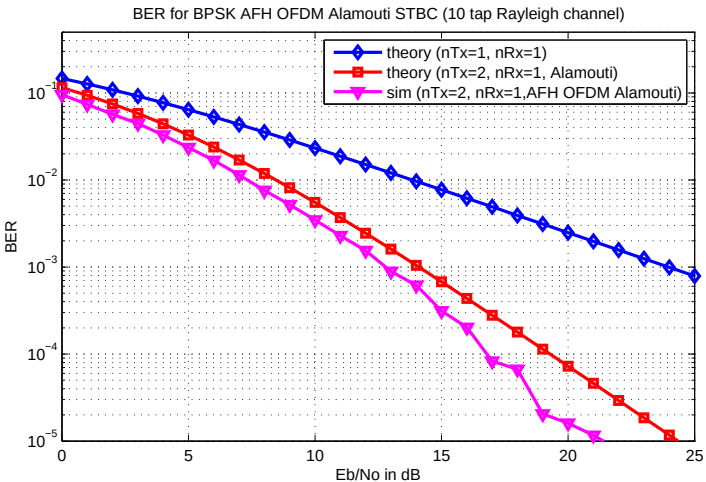
Result for OFDM Alamouti-Coded 16-QAM



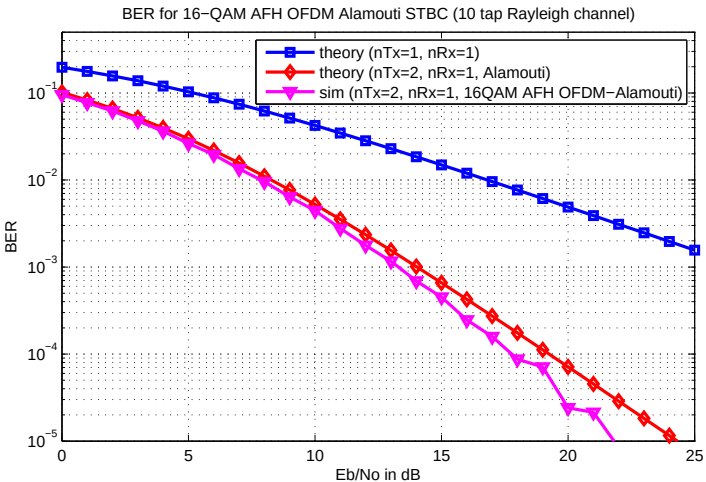
AFH Alamouti-Coded OFDM

- Information is fed back about the channel conditions to the transmitter
- Channel Condition is calculated separately for channels across the two antennas
- Adaptive Hopping pattern is independent for both the antenna

Result for AFH OFDM Alamouti-Coded BPSK



Result for AFH OFDM Alamouti-Coded 16-QAM



Conclusions

- The system model proposed achieves higher gain due to diversity
- Performance of AFH Alamouti-Coded OFDM improves by 0 to 5 dB as compared to Alamouti coded OFDM
- Performance of AFH OFDM improves by 0 to 5 dB as compared to OFDM
- Performance of AFH Alamouti-Coded OFDM improves by 0 to 12 dB as compared to that of OFDM

Future Work

- The proposed scheme can be incorporated onto MIMO (Multiple Input Multiple Output) systems
- It can also be applied in multiuser scenario

THANK YOU !