Chapter 7
Adaptive OFDM

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  - 7.3 Adaptive Single- and Multi-user OFDM

Introduction

- ☞ **The bit error probability of different OFDM subcarriers transmitted in time dispersive channels depends on the frequency domain channel transfer function.**
- ☞ **If the subcarriers that will exhibit high bit error probabilities in the OFDM symbol to be transmitted can be identified and excluded from data transmission, the overall BER can be improved in exchange for a slight loss of system throughput.**
- ☞ **As the frequency domain fading deteriorates the SNR of certain subcarriers, but improves other subcarriers above the average SNR value, the potential loss of throughput due to the exclusion of faded subcarriers can be mitigated by employing higher order modulation modes on the subcarriers exhibiting high SNR values.**

Introduction

- In addition to excluding sets of faded subcarriers and varying the modulation modes employed, other parameters such as the coding rate of error correction coding schemes can be adapted at the transmitter according to the perceived channel transfer function.
- Adaptation of the transmission parameters is based on the transmitter's perception of the channel conditions in the forthcoming timeslot.
- This estimation of future channel parameters can only be obtained by extrapolation of previous channel estimations, which are acquired upon detecting each received OFDM symbol. The channel characteristics therefore have to be varying sufficiently slowly compared to the estimation interval.

Introduction

- Adapting the transmission technique to the channel conditions on a timeslot–by–timeslot basis for serial modems in narrowband fading channels has been shown to considerably improve the BER performance.
- The Doppler fading rate of the narrow–band channel has a strong effect on the achievable system performance, if the fading is rapid, then the prediction of the channel conditions for the next transmit timeslot is inaccurate, and therefore the wrong set of transmission parameters may be chosen.

Adaptive Techniques

- **Adaptive modulation is only suitable for duplex communication between two stations, since the transmission parameters have to be adapted using some form of two–way transmission in order to allow channel measurements and signalling to take place.**
- **Transmission parameter adaptation is a response of the transmitter to time–varying channel conditions.**

Adaptive Techniques

- **In order to efficiently react to the changes in channel quality, the following steps have to be taken:**
  - **Channel quality estimation: In order to appropriately select the transmission parameters to be employed for the next transmission, a reliable estimation of the channel transfer function during the next active transmit timeslot is necessary.**
  - **Choice of the appropriate parameters for the next transmission: Based on the prediction of the channel conditions for the next timeslot, the transmitter has to select the appropriate modulation modes for the subcarriers.**
  - **Signalling or blind detection of the employed parameters: The receiver has to be informed, as to which demodulator parameters to employ for the received packet. This information can either be conveyed within the OFDM symbol itself, at the cost of loss of effective data throughput, or the receiver can attempt to estimate the parameters employed by the remote transmitter by means of blind detection mechanisms.**

Adaptive Techniques

- **Channel quality estimation**
  - **The transmitter requires an estimate of the expected channel conditions for the time when the next OFDM symbol is to be transmitted.**
  - **Since this knowledge can only be gained by prediction from past channel quality estimations, the adaptive system can only operate efficiently in an environment exhibiting relatively slowly varying channel conditions.**

Adaptive Techniques - Channel Quality Estimation

channel quality estimation

open–loop adaptation

- If the communication between the two stations is bidirectional and the channel can be considered reciprocal, then each station can estimate the channel quality on the basis of the received OFDM symbols, and adapt the parameters of the local transmitter to this estimation.
- There is no feedback between the receiver of a given OFDM symbol and the choice of the modulation parameters.
- For example : Time Division Duplex (TDD) System

closed–loop adaptation

- If the channel is not reciprocal, as in a Frequency Division Duplex (FDD) system, then the stations cannot determine the parameters for the next OFDM symbol's transmission from the received symbols.
- The receiver has to estimate the channel quality and explicitly signal this perceived channel quality information to the transmitter in the reverse link.
- If the communication between the stations is essentially unidirectional, then a low–rate signalling channel must be implemented from the receiver to the transmitter. If such a channel exists, then the same technique as for non-reciprocal
- channels can be employed.

Adaptive Techniques - Channel Quality Estimation

- **For OFDM modems, the bit error probability in each subcarrier is determined by the fluctuations of the channel's instantaneous frequency domain channel transfer function Hn, if no interference is present. The estimate of the channel transfer function ^Hn can be acquired by means of pilot–tone based channel estimation,**
- **More accurate measures of the channel transfer function can be gained by means of decision–directed or time–domain training sequence based techniques.**
- **The estimate of the channel transfer function ˆ Hn does not take into account effects, such as co–channel or inter–subcarrier interference.**
- **Alternative channel quality measures including interference effects can be devised on the basis of the error correction decoder's soft output information or by means of decision-feedback local SNR estimations.**
- **The delay between the channel quality estimation and the actual transmission of the OFDM symbol in relation to the maximal Doppler frequency of the channel is crucial as regards to the adaptive system's performance.**

Adaptive Techniques - Channel Quality Estimation

- **For a closed–loop adaptive system the delays between channel estimation and transmission of the packet are generally longer than for an open–loop adaptive system, and therefore the Doppler frequency of the channel is a more critical parameter for the system's performance than in the context of open–loop adaptive systems.**

Adaptive Techniques- Parameter Adaptation

- **Parameter adaptation**
  - **Different transmission parameters can be adapted to the anticipated channel conditions, such as the modulation and coding modes.**
  - **The adaptive channel coding parameters entail code rate, adaptive interleaving and puncturing for convolutional and turbo codes, or varying block lengths for block codes.**
  - **Based on the estimated frequency–domain channel transfer function, spectral pre–distortion at the transmitter of one or both communicating stations can be invoked, in order to partially of fully counteract the frequency–selective fading of the time– dispersive channel.**
  - **In addition to improving the system's BER performance in time–dispersive channels, spectral pre–distortion can be employed in order to perform all channel estimation and equalization functions at only one of the two communicating duplex stations.**

Adaptive Techniques- Parameter Adaptation

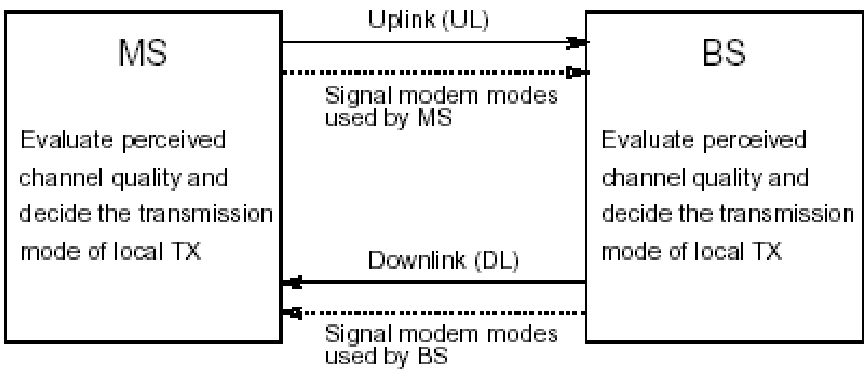
- **Low–cost, low power consumption mobile stations can communicate with a base station that performs the channel estimation and frequency–domain equalization of the uplink, and uses the estimated channel transfer function for pre–distorting the down–link OFDM symbol.**
- **This setup would lead to different overall channel quality on the up– and downlink, and the superior downlink channel quality could be exploited by using a computationally less complex channel decoder having weaker error correction capabilities in the mobile station than in the base station.**

Adaptive Techniques - Signalling the Parameters

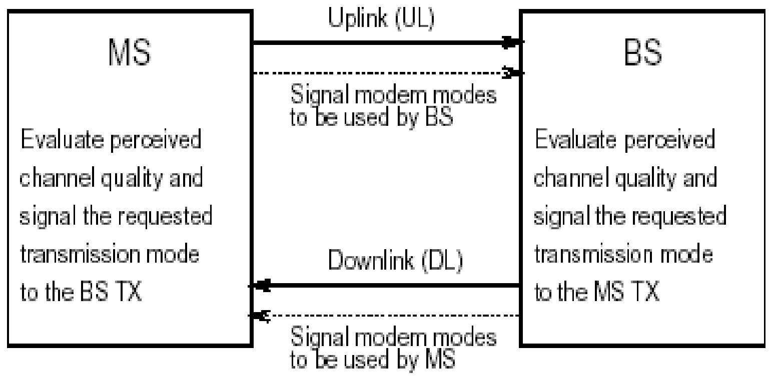
Signalling the parameters

- Signalling plays an important role in adaptive systems and the range of signalling options.
- If the channel quality estimation and parameter adaptation have been performed at the transmitter of a particular link, based on open–loop adaptation, then the resulting set of parameters has to be communicated to the receiver in order to successfully demodulate and decode the OFDM symbol.
- If the receiver itself determines the requested parameter set to be used by the remote transmitter — the closed–loop scenario — then the same amount of information has to be transported to the remote transmitter in the reverse link.
- If this signalling information is corrupted, then the receiver is generally unable to correctly decode the OFDM symbol corresponding to the incorrect signalling information.
- Efficient and reliable signalling techniques have to be employed for practical implementation of adaptive OFDM modems.

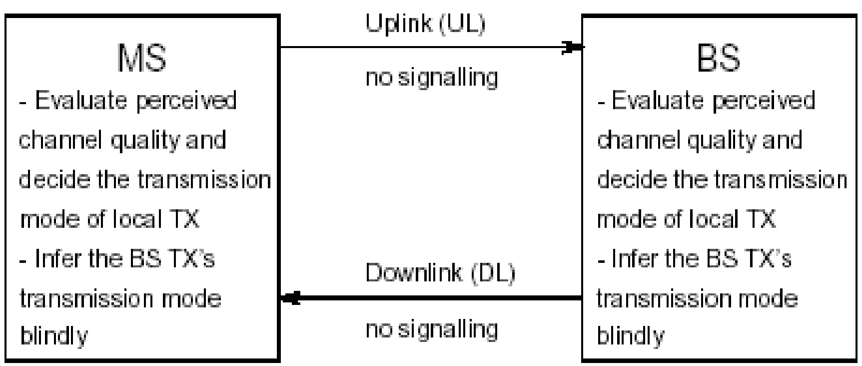
Adaptive Techniques - Signalling the Parameters



(a) Reciprocal channel, open–loop control



(b) Non–reciprocal channel, closed–loop signalling

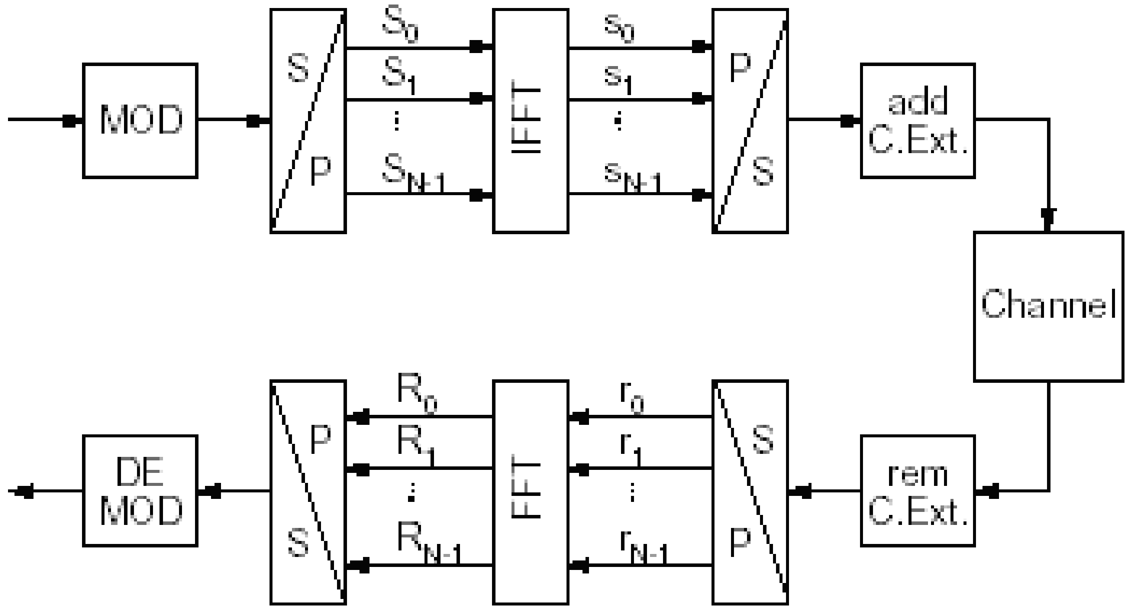


(c) Reciprocal channel, blind modem–mode detection

Figure : Signalling scenarios in adaptive modems

Adaptive Modulation of OFDM

☞ **A: System Model**



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Adaptive Modulation of OFDM

- **At the transmitter, the modulator generates *N* data symbols $S_n,\ 0 \le n \le N-1$, which are multiplexed to the N subcarriers.**
- The time-domain samples s_n transmitted during one OFDM symbol are generated by the inverse fast Fourier transform (IFFT) and transmitted over the channel after the cyclic extension (C. Ext.) has been inserted.
- The channel is modeled by its time-variant impulse response $h(\tau, t)$ and additive white Gaussian noise (AWGN).
- At the receiver, the cyclic extension is removed from the received time-domain samples, and the data samples r_n are fast Fourier transformed (FFT), in order to yield the received frequency-domain data symbols R_n .

Adaptive Modulation of OFDM

- The received data symbols R_n can be expressed as

$$R_n = S_n \cdot H_n + n_n$$

,where n_n is an AWGN sample.

- Coherent detection is assumed for the system, and the estimate $\hat{H}_n$ can be obtained by the use of pilot subcarriers in the OFDM symbol, or by employing time-domain channel sounding training sequences embedded in the transmitted signal.
- Since the noise energy in each subcarrier is independent of the channel's frequency domain transfer function H_n, the local signal-to-noise ratio (SNR) in subcarrier can be expressed as

$$\gamma_n = \left|H_n\right|^2 \cdot \gamma$$

,where γ is the overall SNR.

Adaptive Modulation of OFDM

- ☞ The goal of adaptive modulation is to choose the appropriate modulation mode for transmission in each subcarrier, given the local SNR γ_n , in order to achieve a good tradeoff between throughput and overall BER.
- ☞ The acceptable overall BER varies depending on other systems parameters, such as the coding rate of the error correction coding, and the nature of the service supported by this particular link.

Adaptive Modulation of OFDM

B: Channel Model

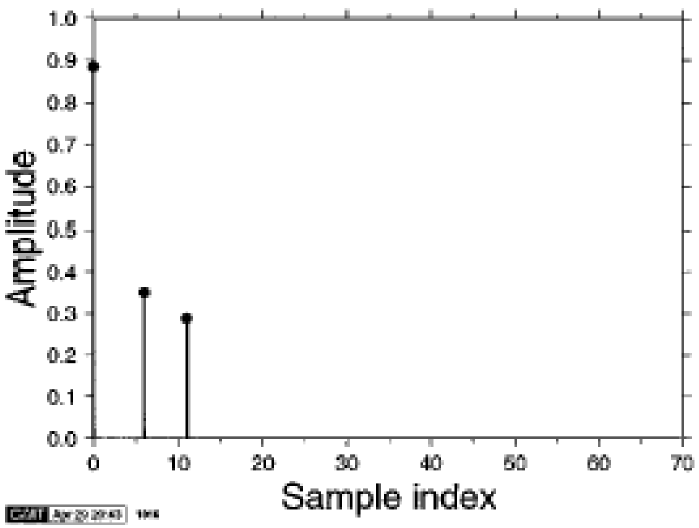
- Each impulses is faded by obeying a Rayleigh distribution of a normalized maximal Doppler frequency of $f_d' = 1.235 \cdot 10^{-5}$, where the normalization time duration was the length of the OFDM symbol, rather than the input bit duration.

Adaptive Modulation of OFDM

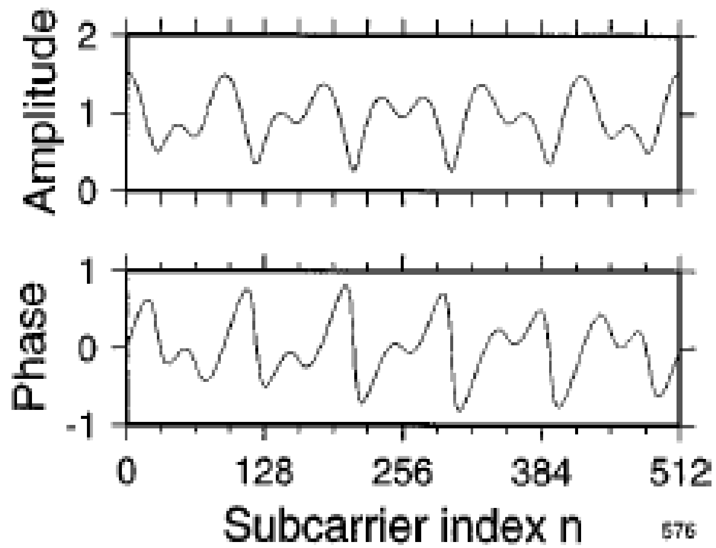
Wideband channel:

(a) unfaded symbol spaced impulse response and

(b) corresponding frequency domain channel transfer function.



(a)



(b)

Adaptive Modulation of OFDM

C: Channel Estimation

- The channel estimation on the basis of the received symbol can be performed by pilot symbol assisted modulation (PSAM), or upon invoking more sophisticated methods, such as decision-directed channel estimation.
- We will initially assume perfect knowledge of the channel transfer function during the received timeslot.

Adaptive Modulation of OFDM

D: Choice of the Modulation Scheme

- The two communicating stations use the open-loop predicted channel transfer function acquired from the most recent received OFDM symbol, in order to allocate the appropriate modulation modes to the subcarriers.
- The modulation scheme was chosen from the set of Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 16-level Quadrature Amplitude Modulation (16-QAM), as well as "No Transmission," for which no signal was transmitted.
- These modulation schemes are denoted by M_m, where $m \in (0,1,2,4)$ is the number of data bits associated with a subcarrier.
- In order to keep the system complexity low, the modulation scheme is not varied on a subcarrier-by-subcarrier basis, but instead the total OFDM bandwidth of 512 subcarriers is split into blocks of adjacent subcarriers, referred to as subbands, and the same modulation scheme is employed for all subcarriers of the same subband.

Adaptive Modulation of OFDM

- **Three modulation scheme allocation algorithms were investigated in the subbands**
  - **Fixed Threshold Adaptation Algorithm**
  - **Subband BER Estimator Adaptation Algorithm**
  - **Constant Throughput Adaptive OFDM**

Adaptive Modulation of OFDM

Fixed Threshold Adaptation Algorithm

- The fixed threshold algorithm was derived from the adaptation algorithm proposed by Torrance for serial modems.
- the channel quality is assumed to be constant for all symbols in the time slot
- channel has to be slowly varying in order to allow accurate channel quality prediction.
- all data symbols in the transmit time slot employ the same modulation scheme, chosen according to the predicted SNR.
- The SNR thresholds for a given long-term target BER were determined by Powell optimization.
- Torrance assumed two uncoded target BERs: 1% for a high data rate "speech" system, and 10^{-4} for a higher integrity, lower data rate "data" system.

Adaptive Modulation of OFDM

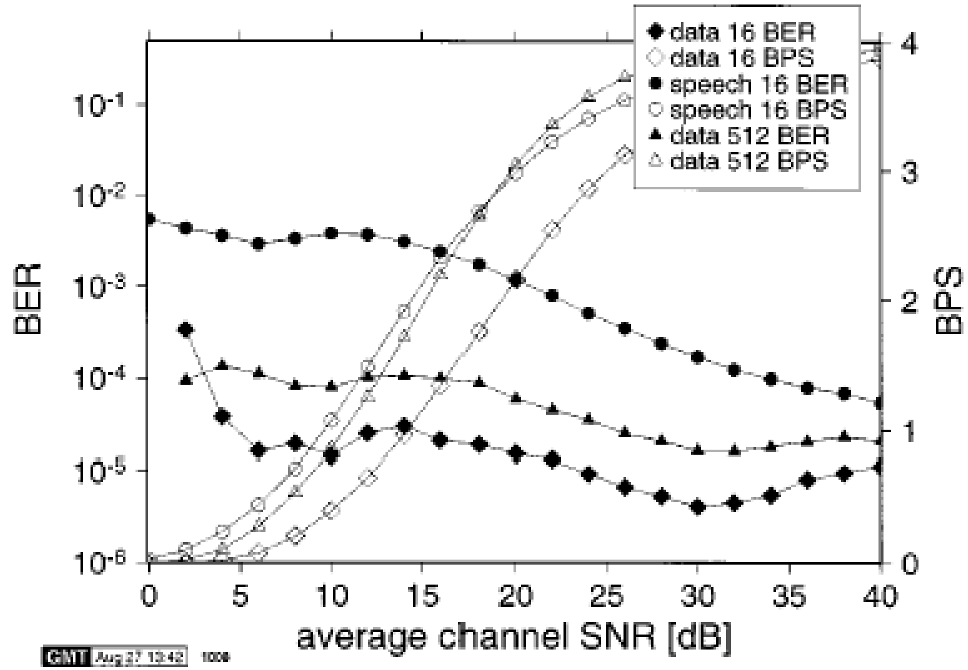
- The modulation scheme M_n is selected, if the instantaneous channel SNR exceeds the switching level l_n .
- For subband adaptive OFDM transmission this implies that if the subband width is wider, than the channel's coherence bandwidth, the above switching algorithm cannot be employed.

TABLE I
OPTIMIZED SWITCHING LEVELS FOR ADAPTIVE MODULATION OVER RAYLEIGH FADING CHANNELS FOR THE "SPEECH" AND "DATA" SYSTEM, SHOWN IN INSTANTANEOUS CHANNEL SNR [dB] (FROM [36])

	l_0	l_1	l_2	l_4
speech system	$-\infty$	3.31	6.48	11.61
data system	$-\infty$	7.98	10.42	16.76

Adaptive Modulation of OFDM

- **The performance of the 16 subband adaptive system over the WATM Rayleigh fading channel**



BER and throughput performance of the 16 subband 512 subcarrier switching level adaptive OFDM modem employing BPSK, QPSK, 16-QAM and“no transmission” over the Rayleigh-fading time dispersive channel

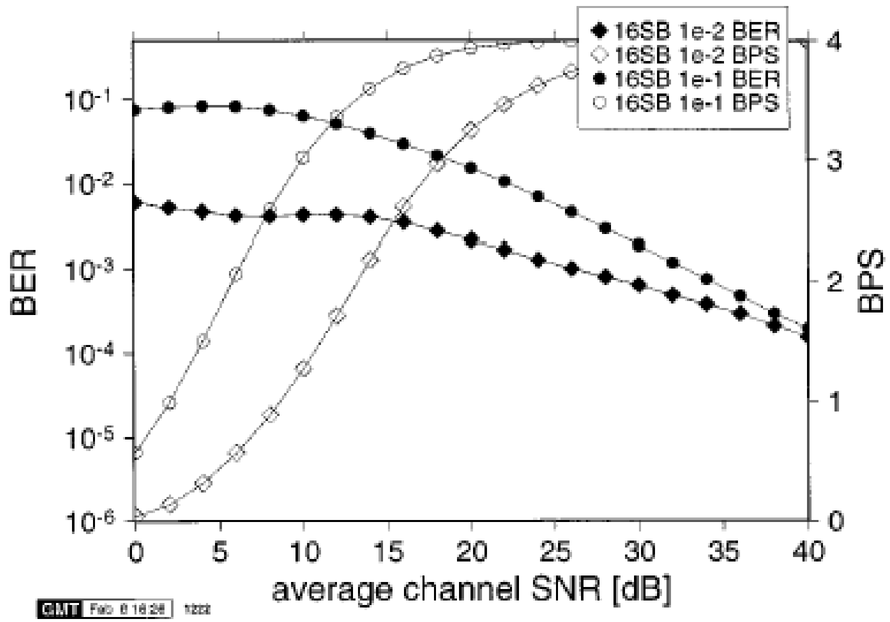
Adaptive Modulation of OFDM

☞Subband BER Estimator Adaptation Algorithm

- An alternative scheme taking into account the nonconstant SNR values γ_j across the N_s subcarriers in the *j*-th subband can be devised by calculating the expected overall bit error probability for all available modulation schemes M_n in each subband, which is denoted by $\bar{p}_e(n) = \frac{1}{N_s}\sum_j p_e(\gamma_j, M_n)$.
- For each subband, the scheme with the highest throughput, whose estimated BER is lower than a given threshold, is then chosen.
- While the adaptation granularity is still limited to the subband width, the channel quality estimation includes not only the worst subcarrier, which leads to an improved throughput.

Adaptive Modulation of OFDM

- the BER and throughput performance for the 16 subband adaptive OFDM modem employing the BER estimator adaptation algorithm in the Rayleigh fading time dispersive channel.



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Adaptive Modulation of OFDM

☞Constant Throughput Adaptive OFDM

- **The time-varying data throughput of an adaptive OFDM modem operating with either of the two adaptation algorithms discussed above makes it difficult to employ such a scheme in a wide variety of applications.**
- **Real-time audio or video transmission is very sensitive to delays, and therefore different adaptation algorithms are needed for such applications.**
- **The constant throughput AOFDM scheme proposed here exploits the frequency selectivity of the channel, while offering a constant bit rate.**
- **The modulation scheme allocation of the subbands is performed on the basis of a cost function, based on the expected number of bit errors in each subband. The expected number of bit errors, $e_{n,s}$, for each subband *n* and each possible modulation scheme mode *s*, is calculated on the basis of the estimated channel transfer function $\hat{H}$, as well as a function of the number of bits transmitted per subband and modulation scheme, $b_{n,s}$.**
- **Each subband is assigned a state variable S_n holding the index of a modulation scheme.**

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Adaptive Modulation of OFDM

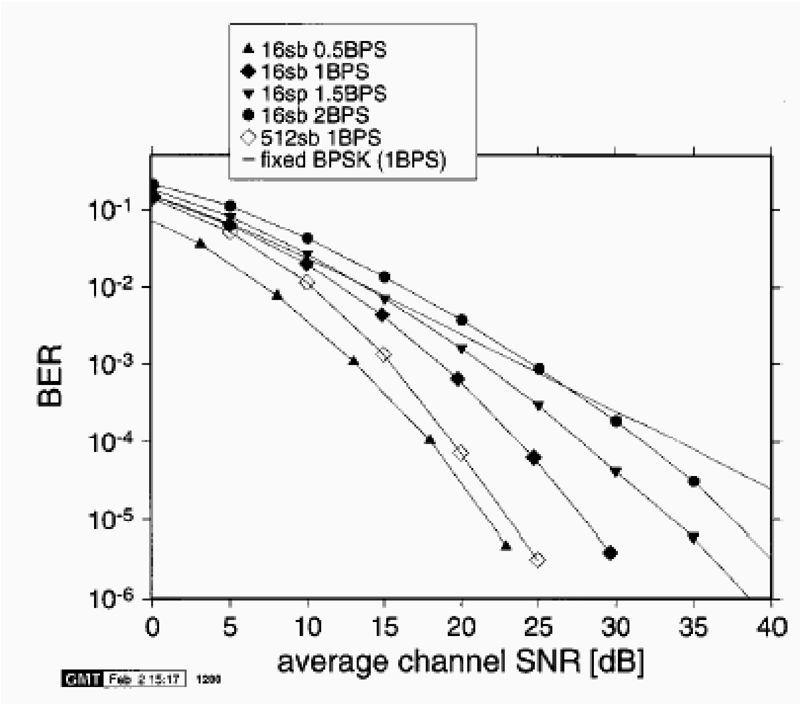
- Each state variable is initialed to the lowest order modulation scheme, which in our case is 0 for "no transmission."
- A set of cost values is calculated for each subband and state as follows:

$$c_{n,s} = \frac{e_{n,s+1} - e_{n,s}}{b_{n,s+1} - b_{n,s}}$$

  for all but the highest level modulation index ***s*****.**
- This cost value is related to the expected increase in the number of bit errors, divided by the increase of throughput, if the modulation scheme having the next higher index is used instead of index *s* in subband *n*.
- The modulation scheme adaptation is performed by repeatedly searching for the block having the lowest value c_{n,s_n} of and incrementing its state s_n . This is repeated, until the total number of bits in the OFDM symbol reaches the target number of bits.

Adaptive Modulation of OFDM

☞BER performance versus SNR for the 512 subcarrier 16 subband constant throughput adaptive OFDM modem employing BPSK, QPSK, 16-QAM, and "no transmission" over the Rayleigh fading time dispersive channel of Fig. 3 for 0.5, 1, 1.5, and 2 BPS target throughput.



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Adaptive Single- and Multi- user OFDM

- Sub-carriers are assigned to the users based on instantaneous channel information, this approach will allow all the sub-carriers to be used more effectively because a sub-carrier will be left unused only if it appears to be in deep fade to all users.
- The main idea is to minimize the overall transmit power by allocating the sub-carriers to the users and by determining the number of bits and the power level transmitted on each sub-carrier based on instantaneous fading characteristics of all users.
- Using TDD mode to know the instantaneous channel characteristics of all the BS-to-MS links based on the received uplink transmissions.
- To reduce the overhead, we can assign a contiguous band of sub-carriers with similar fading characteristics as a group, instead of assigning each individual sub-carrier.

Multi-user OFDM with Adaptive Sub-carrier, Bit, and Power Allocation

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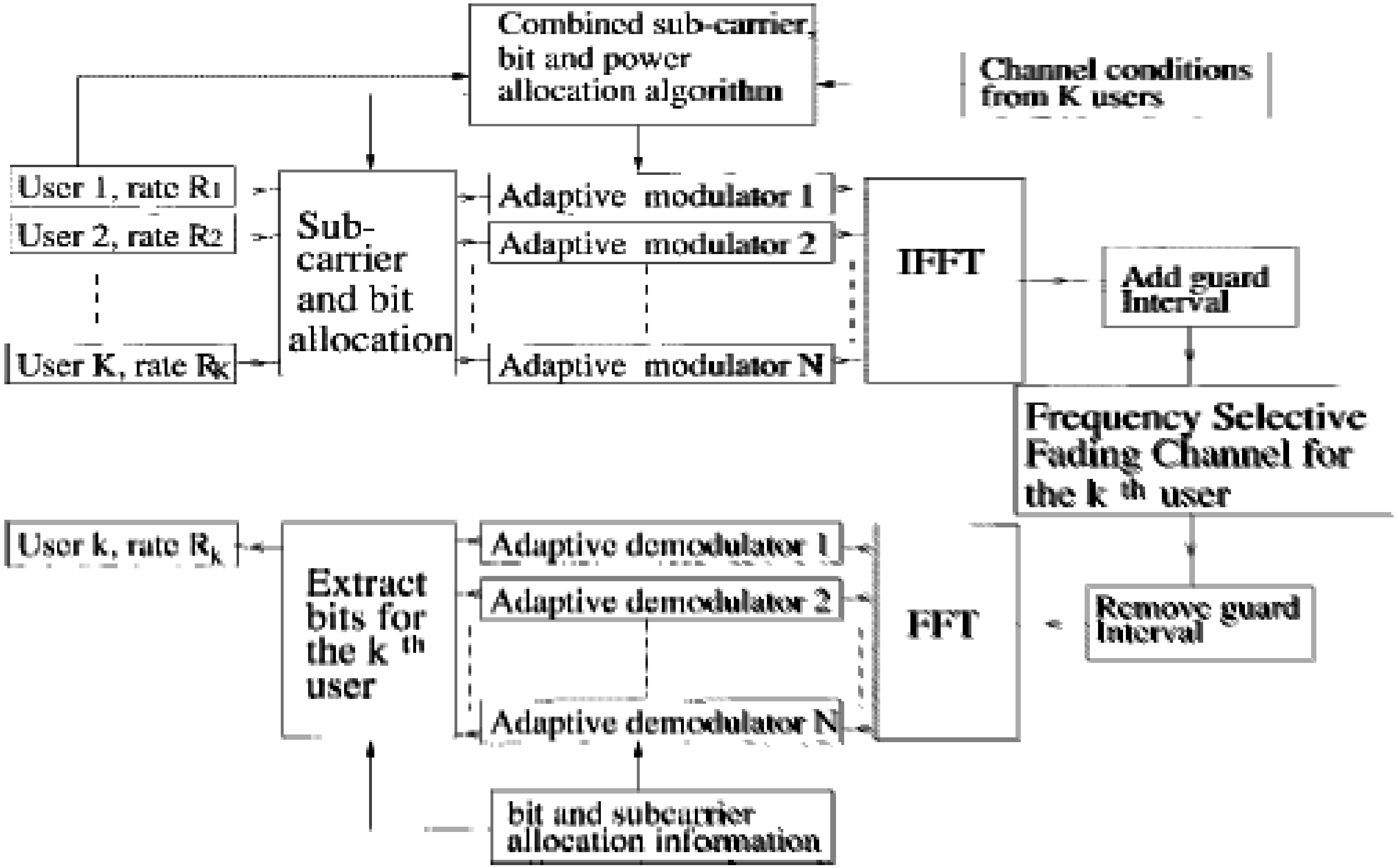
Multi-user OFDM with Adaptive Sub-carrier, Bit, and Power Allocation

- **Minimizing the overall transmit power by adaptively assigning sub-carriers to the users along with the number of bits and power level to each sub-carriers.**
- **Given the instantaneous channel information, the algorithm obtains a sub-optimal sub-carrier allocation, and then single-user bit allocation is applied on the allocated sub-carriers.**

Multi-user OFDM with Adaptive Sub-carrier, Bit, and Power Allocation

☞ System Model



Multi-user OFDM with Adaptive Sub-carrier, Bit, and Power Allocation

☞ System Model

R_k : *Data rate bits per OFDM symbol of kth user.*

$c_{k,n}$ *to be the number of bits of kth user that are assigned to the nth subcarrier.*

For each n, $c_{k',n} \neq 0 \rightarrow c_{k,n} = 0 \;\; \forall k \neq k'.$

$c_{k,n} \leftarrow D = [0,1,2,\cdots,M].$

$f_k(c)$: *the required received power in a subcarrier for a reliable reception c information bit/symbol when the channel gain is equal to unity.*

$P_{k,n} = \dfrac{f_k(c_{k,n})}{\alpha_{k,n}^2}$: *In the received side, the transmitted power, allocated to the nth subcarrier by the kth user.*

Multi-user OFDM with Adaptive Sub-carrier, Bit, and Power Allocation

☞ Bit Allocation Algorithm for Single user channel

$$P_T^* = \min_{c_{k,n} \in \mathbf{D}} \sum_{n=1}^{N} \sum_{k=1}^{K} \frac{1}{\alpha_{k,n}^2} f_k(c_{k,n})$$

and the minimization is subjected to the constraints

C1: For all $k \in \{1, \ldots, K\}$, $R_k = \sum_{n=1}^{N} c_{k,n}$

and

C2: For all $n \in \{1, \ldots, N\}$,
if there exists k' with $c_{k',n} \neq 0$, then $c_{k,n} = 0$,
$\forall k \neq k'$.

Multi-user OFDM with Adaptive Sub-carrier, Bit, and Power Allocation

☞ Bit Allocation Algorithm for Single user channel

$$P_T^* = \min_{c_n \in D} \sum_{n=1}^{N} \frac{1}{\alpha_n^2} f(c_n)$$

and the minimization is under the constraint

$$R = \sum_{n=1}^{N} c_n.$$

Initialization:

For all n, let $c_n = 0$ and $\Delta P_n = [f(1) - f(0)]/\alpha_n^2$;

Bit Assignment Iterations:

Repeat the following R times:

$\hat{n} = \arg\min_n \Delta P_n$;

$c_{\hat{n}} = c_{\hat{n}} + 1$;

$\Delta P_{\hat{n}} = [f(c_{\hat{n}} + 1) - f(c_{\hat{n}})]/\alpha_{\hat{n}}^2$;

End;

Finish:

$\{c_n\}_{n=1}^{N}$ is the final bit allocation solution.

Multi-user OFDM with Adaptive Sub-carrier, Bit, and Power Allocation

☞ Multi-user Sub-carrier and Bit Allocation

$$P_T = \min_{\substack{c_{k,n} \in [0, M] \\ \rho_{k,n} \in [0,1]}} \sum_{n=1}^{N} \sum_{k=1}^{K} \frac{\rho_{k,n}}{\alpha_{k,n}^2} f_k(c_{k,n})$$

where $c_{k,n}$ and $\rho_{k,n}$ have to satisfy

$$R_k = \sum_{n=1}^{N} \rho_{k,n} c_{k,n}, \qquad \text{for all } k \in \{1, \ldots, K\}$$

and

$$1 = \sum_{k=1}^{K} \rho_{k,n}, \qquad \text{for all } n \in \{1, \ldots, N\}.$$

For any valid set of $c_{k,n} \in \mathbf{D}$ satisfying the constraints and (4) in the original optimization problem, we can let

$$\rho_{k,n} = \begin{cases} 1, & \text{if } c_{k,n} \neq 0, \\ 0, & \text{if } c_{k,n} = 0. \end{cases} \qquad ($$

Multi-user OFDM with Adaptive Sub-carrier, Bit, and Power Allocation

☞ Multi-user Sub-carrier and Bit Allocation

$$P_T = \min_{\substack{r_{k,n} \in [0, M\rho_{k,n}] \\ \rho_{k,n} \in [0,1]}} \sum_{n=1}^{N} \sum_{k=1}^{K} \frac{\rho_{k,n}}{\alpha_{k,n}^2} f_k\left(\frac{r_{k,n}}{\rho_{k,n}}\right)$$

where $r_{k,n}$ and $\rho_{k,n}$ have to satisfy

$$R_k = \sum_{n=1}^{N} r_{k,n}, \quad \text{for all } k \in \{1, \ldots, K\}$$

and

$$1 = \sum_{k=1}^{K} \rho_{k,n}, \quad \text{for all } n \in \{1, \ldots, N\}.$$

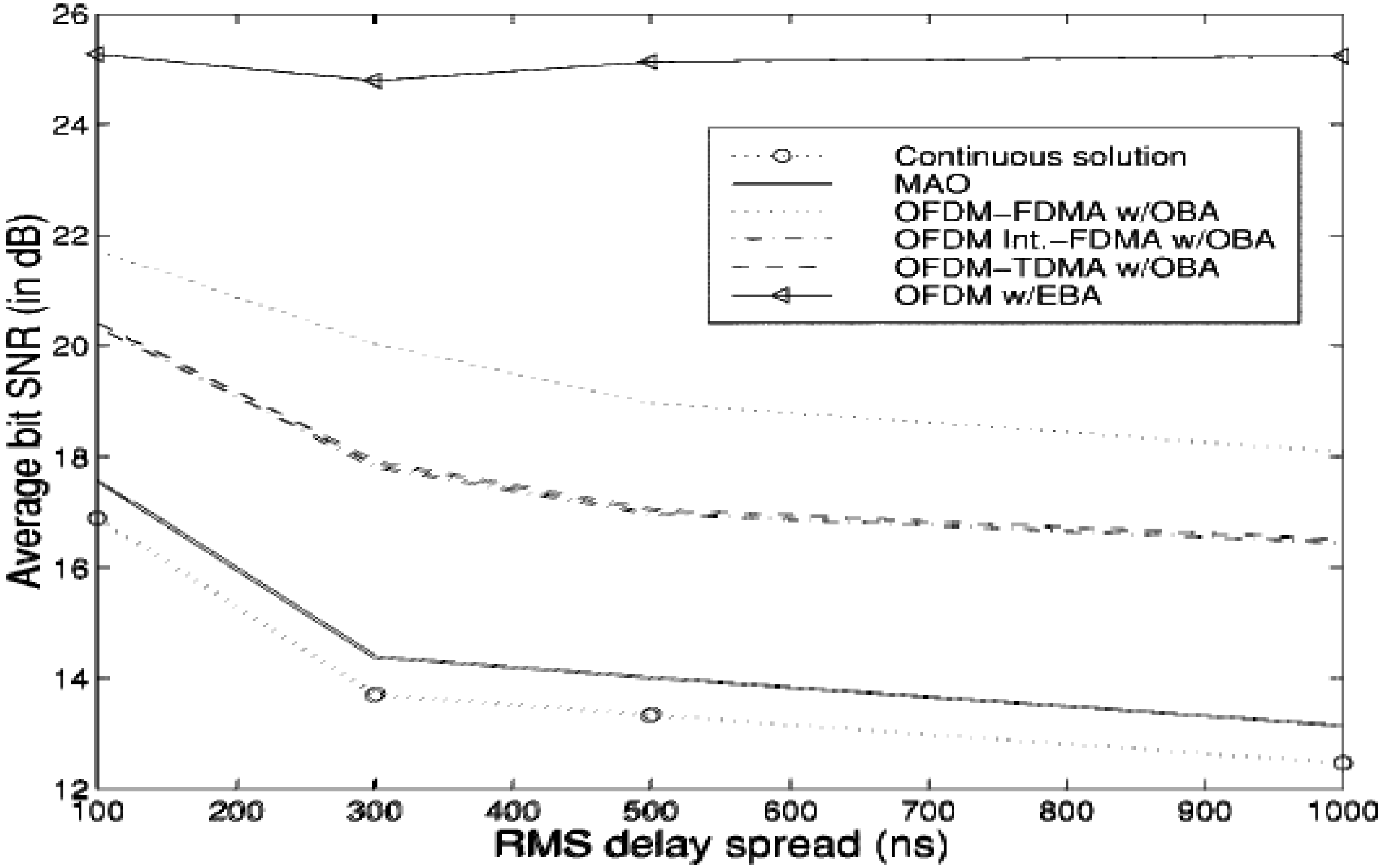
$$L = \sum_{n=1}^{N} \sum_{k=1}^{K} \frac{\rho_{k,n}}{\alpha_{k,n}^2} f_k\left(\frac{r_{k,n}}{\rho_{k,n}}\right) - \sum_{k=1}^{K} \lambda_k \left(\sum_{n=1}^{N} r_{k,n} - R_k\right) - \sum_{n=1}^{N} \beta_n \left(\sum_{k=1}^{K} \rho_{k,n} - 1\right) \quad (14)$$

$$H_{k,n}(\lambda) = \frac{1}{\alpha_{k,n}^2}\left[f_k\left(f_k'^{-1}(\lambda\alpha_{k,n}^2)\right) - \lambda\alpha_{k,n}^2 f_k'^{-1}(\lambda\alpha_{k,n}^2)\right].$$

only the user with the smallest $H_{k,n}(\lambda_{q,k})$ can use that sub-carrier.

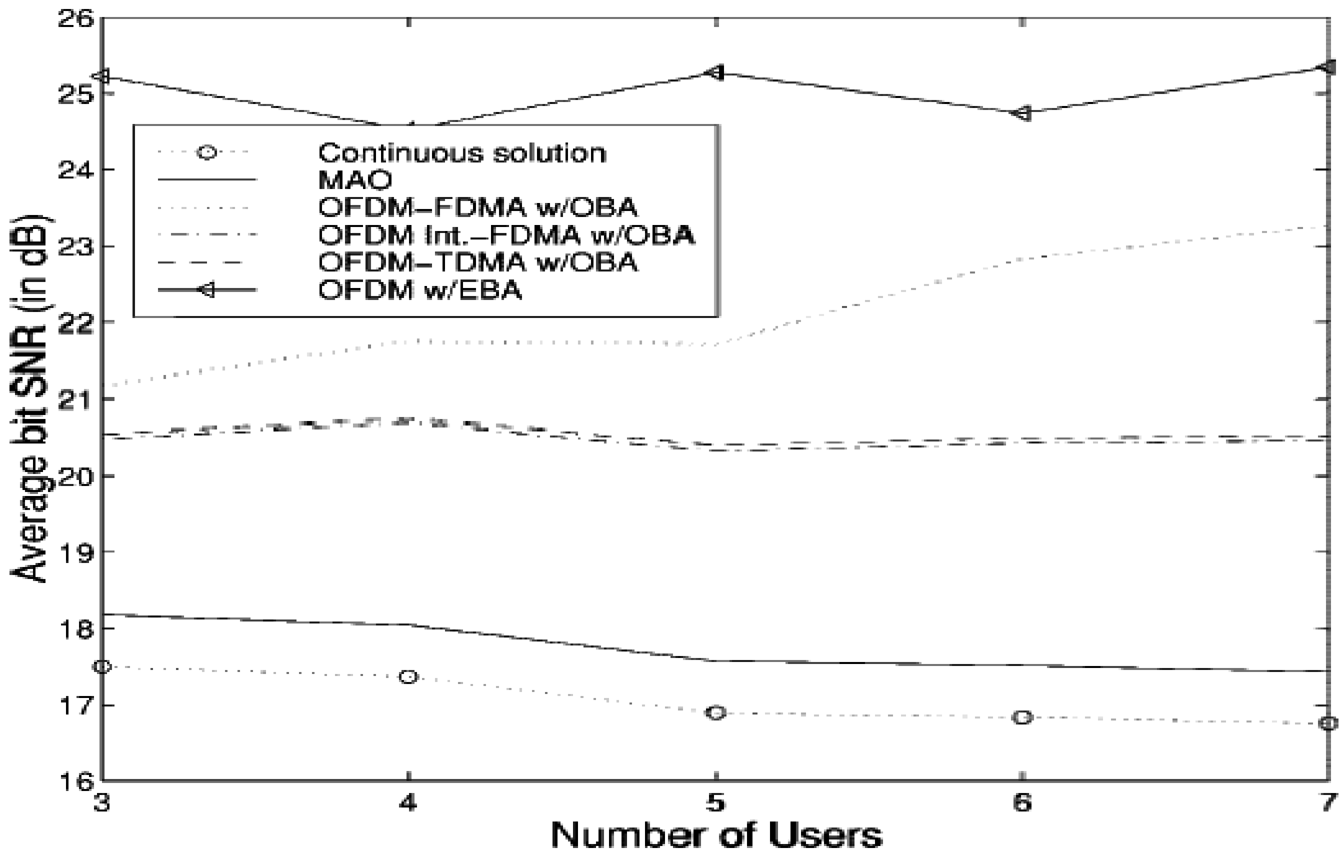
Multi-user OFDM with Adaptive Sub-carrier, Bit, and Power Allocation

☞ **Performance**



Multi-user OFDM with Adaptive Sub-carrier, Bit, and Power Allocation

☞ Performance



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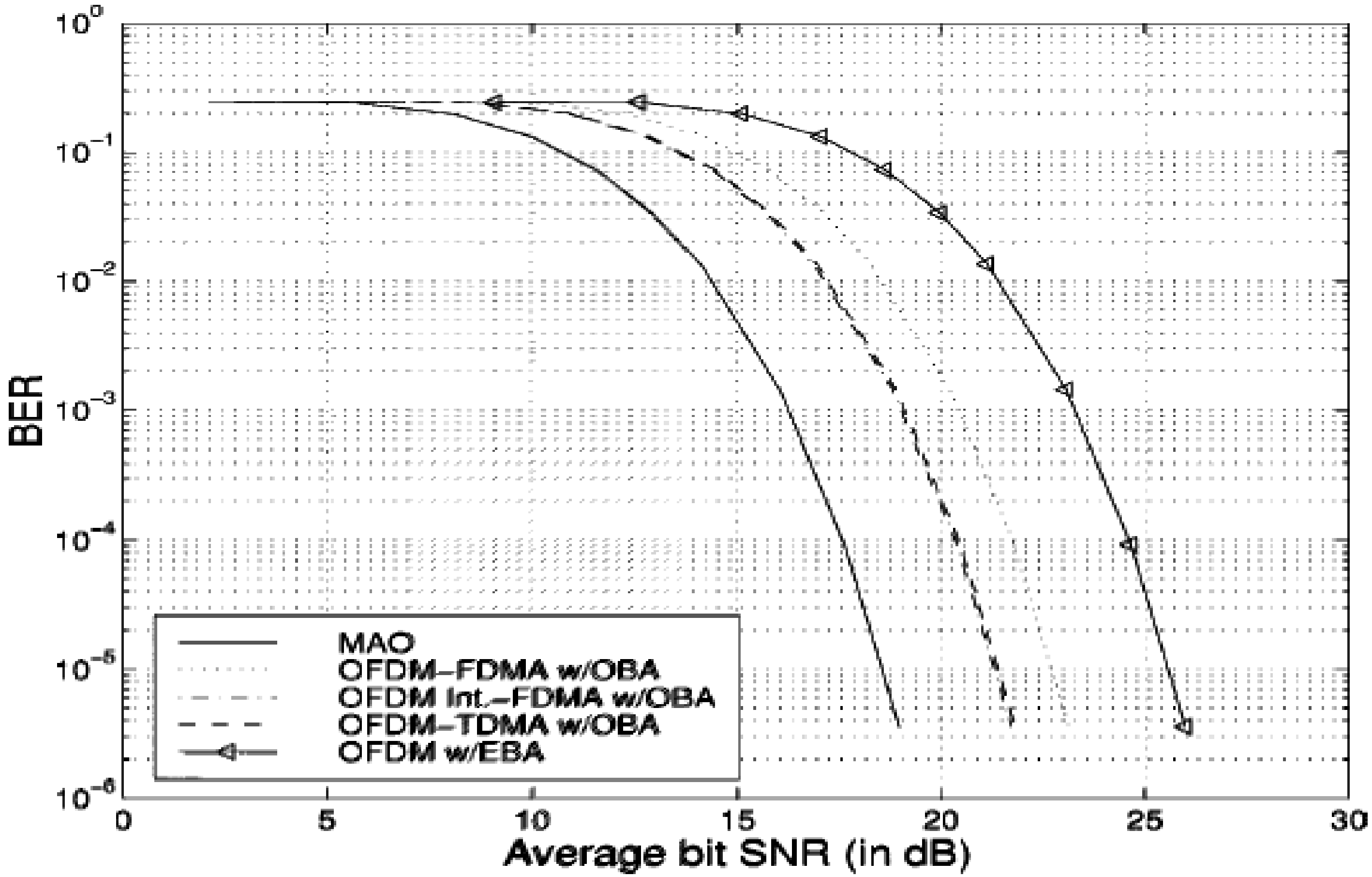
Multi-user OFDM with Adaptive Sub-carrier, Bit, and Power Allocation

☞ Performance



References

☞ **[1] L. Hanzo, W. Webb and T. Keller, *Single- and multi-carrier quadrature amplitude modulation – Principles and applications for personal communications, WLANs and broadcasting*, John Wiley & Sons, Ltd, 2000.**