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Broadband Wireless Access: Technical Challenges, Standards and Technologies

Hikmet Sari

Chief Scientist

SEQUANS Communications

Bat. CitiCenter, 19 Le Parvis

F-92073 Paris La Défense, France

Presentation Outline

- Broadband wireless access and evolution of requirements from fixed to mobile services
- The BWA channel
- WiMAX Forum and IEEE 802.16 specifications
- Transmission and multiple access technologies: OFDM, Single-Carrier Transmission (SCT) and OFDMA
- Multiple antenna (MIMO) options and tradeoffs
- Link adaptation
- Summary and conclusions

Fixed Access Networks

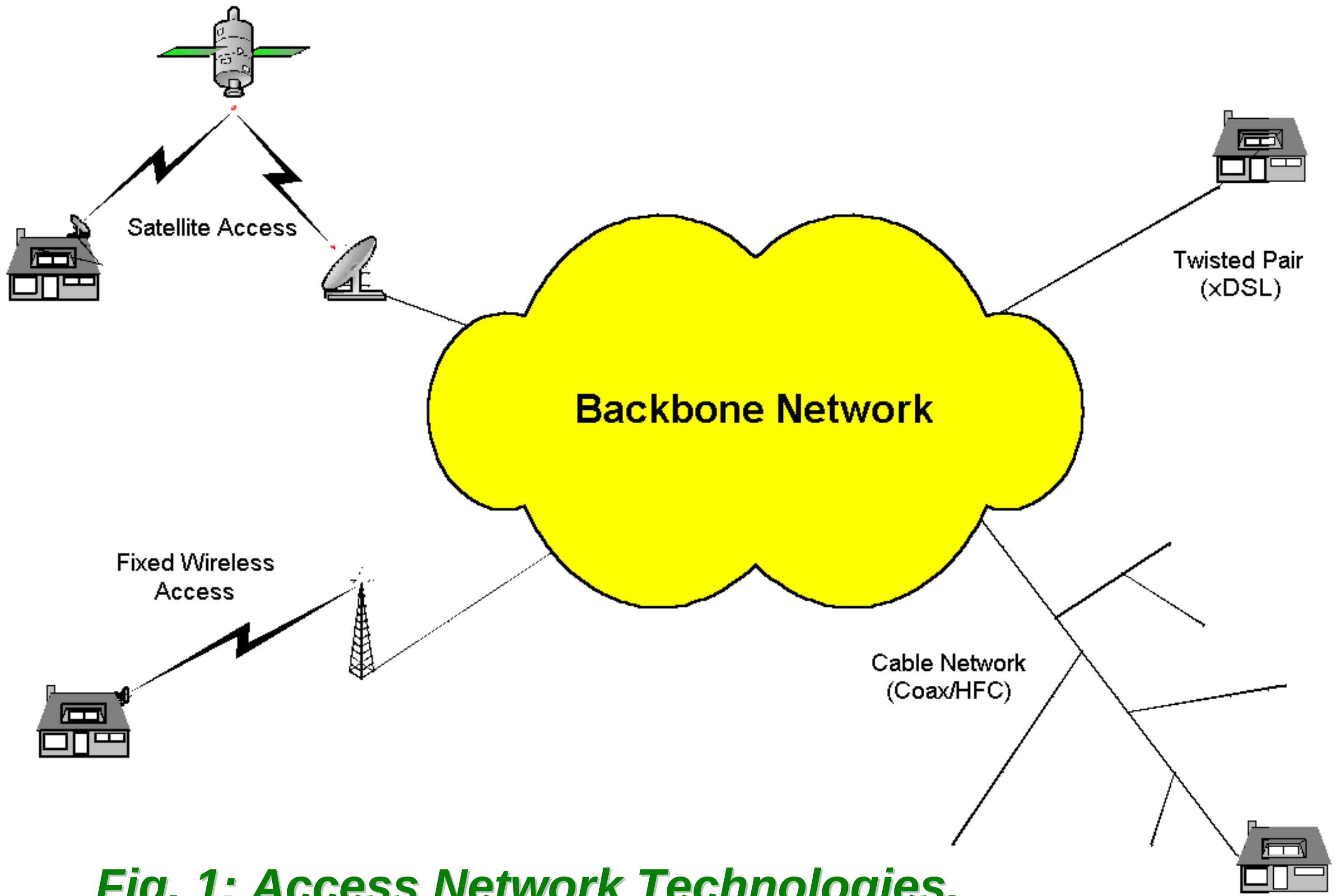
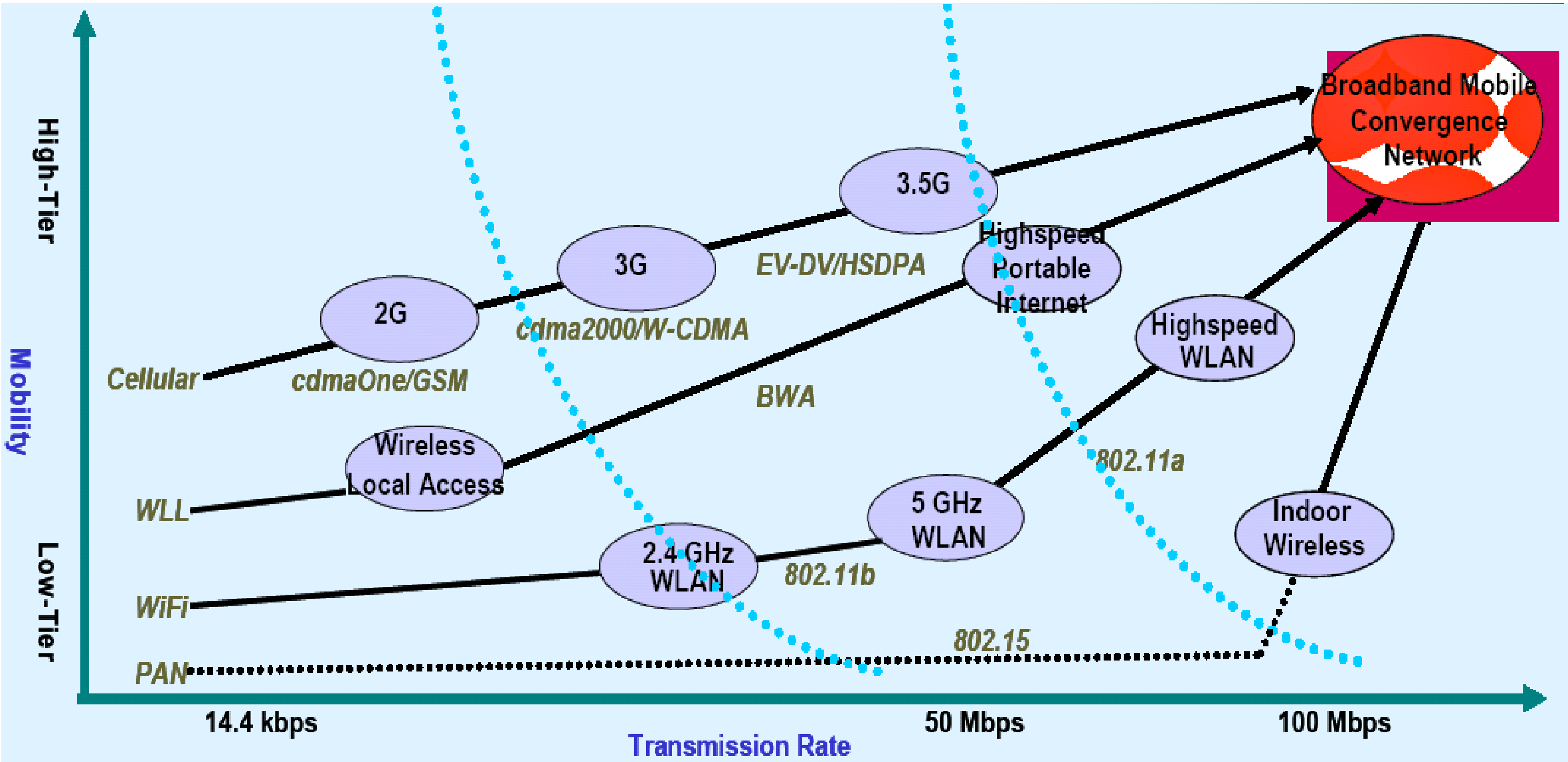


Fig. 1: Access Network Technologies.

Evolution of Wireless Technologies



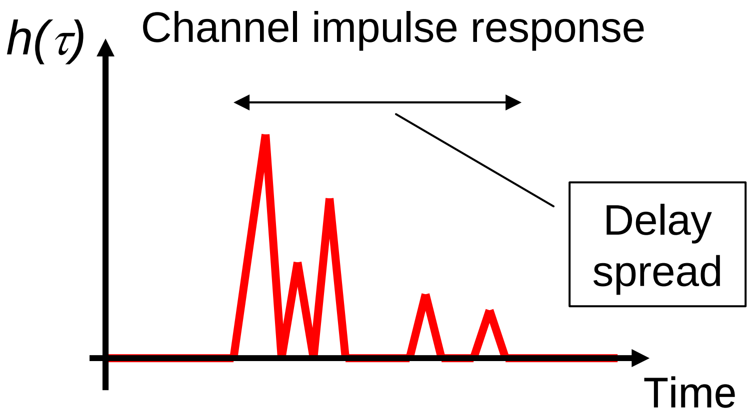
Fixed BWA Systems

- Fixed BWA systems can be designed to operate at millimeter-wave or microwave frequencies.
- They involve a fixed cellular network, where each base station (BS) serves a number of subscribers located in its coverage area.
- Each user is assigned to a predetermined BS, and directional subscriber antennas are pointed to the serving BS during installation.
- At millimeter waves, the cell size does not exceed a few kilometers. Propagation is based on clear line-of-sight (LOS), and signal transmission does not suffer from strong intersymbol interference.

2-11 GHz Frequency Band

- BWA in this frequency band has several distinctive features from BWA at millimeter-wave frequencies.
- First, due to the available transmit power and lower signal attenuation, the cell size typically spans several kilometers or several tens of kilometers.
- Second, the subscriber antenna directivity is much smaller than at millimeter-wave frequencies. The 3 dB beamwidth of subscriber antennas in the 2-11 GHz band is higher than 20°.
- The result is that BWA in the 2-11 GHz band is based on non-LOS propagation, and this incurs a significant amount of multipath that needs to be compensated.

Time-Dispersive Channels



$$h(\tau) = \sum_{k=0}^{N-1} \underbrace{a_k e^{j\theta_k}}_{A_k} \delta(\tau - \tau_k)$$

τ	–	delay
a_k	–	kth tap gain (real)
θ_k	–	kth tap phase offset
A_k	–	kth tap coefficient (complex)
τ_k	–	kth tap delay
$\delta(\bullet)$	–	Dirac delta function

SUI Channel Models

Model	Tap 1	Tap 2	Tap 3	*rms* delay (µs)
SUI 1	0 0	0.4 - 15	0.9 - 20	0.111
SUI 2	0 0	0.4 - 12	1.1 - 15	0.202
SUI 3	0 0	0.4 - 5	0.9 - 10	0.264
SUI 4	0 0	1.5 - 4	4 - 8	1.257
SUI 5	0 0	4 - 5	10 - 10	2.842
SUI 6	0 0	14 - 10	20 - 14	5.240

Discussion

- The channel dispersion in SUI 4 – SUI 6 models covers a large number of symbol periods. On a 7 MHz channel, the symbol period is 178 ns, and the SUI 5 model spans 56 symbol period.
- The SUI 5 model dispersion spans 112 symbol periods over a 14 MHz channel and 224 symbol periods over a 28 MHz channel.
- The numbers above are doubled for the SUI 6 model whose impulse response spans 20 µs.
- Therefore, the transmission technique to be used in these systems must be able to compensate for channel impulse responses spanning hundreds of symbol periods.

IEEE 802.16 and the WiMAX Forum

- The IEEE 802.16 – 2004 specifications define the PHY and MAC layers for fixed BWA systems operating on licensed frequency bands between 2 and 11 GHz. They include 3 PHY layers: OFDM, SCT and OFDMA, but from those, the WiMAX Forum has only selected the OFDM PHY.
- Similarly, the IEEE 802.16e – 2005 specifications define the PHY and MAC layers for mobile BWA systems operating on licensed frequency bands between 2 and 6 GHz. Here too, 3 PHY layers are included, but the WiMAX Forum has selected the OFDMA PHY for mobile applications.

BWA PHY Technologies: OFDM

- OFDM is a multicarrier transmission technique, in which the frequency spacing between adjacent carriers is equal to the inverse of the symbol period.
- An OFDM system with N carriers uses an N-point inverse Discrete Fourier Transform (DFT) at the transmitter and an N-point forward DFT at the receiver.
- The basic idea is to split the total channel bandwidth into N narrow sub-channels with an essentially flat frequency response. To do so, the number of carriers N must be sufficiently large.
- The incoming data symbols are grouped into N-symbol blocks, and each symbol of the block is transmitted at a separate carrier.

Principle of OFDM

- The transmitted symbols are affected by the phase and attenuation of the channel frequency response at the corresponding carrier frequencies.
- Recovery of these symbols on the receiver side requires inversion of the channel frequency response. This is performed using a multiplier bank at the DFT output.
- To suppress the interference between OFDM symbols and make the linear convolution of the channel look like the circular convolution performed by the multiplier bank, a cyclic prefix is inserted between successive OFDM symbols.
- The cyclic prefix, which is pure overhead, is dropped before the DFT at the receiver.

Principle of OFDM (cont'd)

- The decision error probability for a transmitted symbol is a function of the channel attenuation at the carrier frequency at which this symbol is transmitted.
- The symbols transmitted at carrier frequencies with a strong channel attenuation suffer from a high error rate and need to be protected.
- The conventional approach to OFDM on frequency-selective channels is to use error correction coding, which introduces redundancy.
- More recently, the concept of precoding has been proposed. With a precoding that disperses the signal energy over the channel bandwidth, OFDM actually *mimics* single-carrier transmission.

Single-Carrier Transmission

- The conventional approach to digital communications over dispersive channels is single-carrier transmission with time-domain equalization (SCT/TDE).
- Time-domain equalization covers the simple linear transversal equalizers, decision-feedback equalizers, as well as maximum-likelihood sequence estimation.
- These techniques have been in use for decades in voice-band data transmission, digital microwave radio, and more recently in mobile radio systems.
- Although frequency-domain channel equalization was originally introduced in the late 1970s, it was not pursued and quickly disappeared from the literature.

Frequency-Domain Equalization

- In the 1993-95 time period, the present author published several papers which showed that a single-carrier system with frequency-domain equalization (SCT/FDE) is a good alternative to OFDM system.

  - *H. Sari, G.Karam, and I. Jeanclaude, "Channel Equalization and Carrier Synchronization in OFDM systems," presented at the Tirrenia Int. Workshop on Digital Communications, September 1993, Italy.*

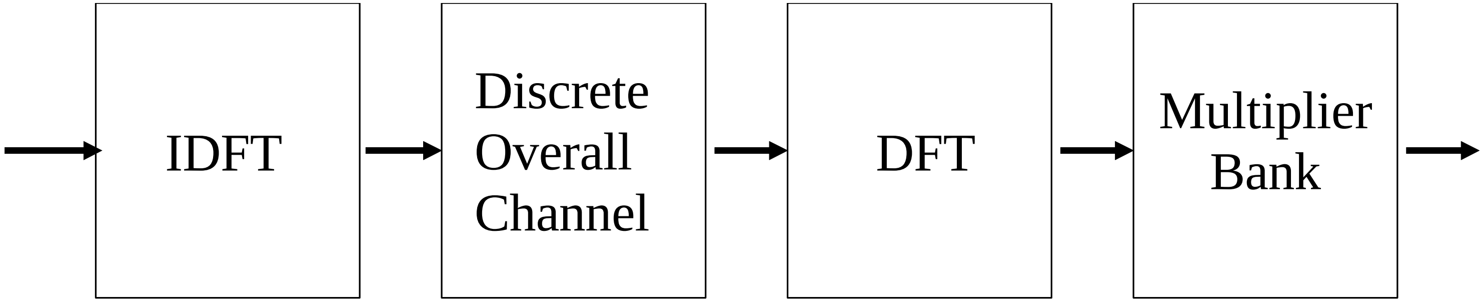
  - *H. Sari, G.Karam, and I. Jeanclaude, "Transmission Techniques for Digital Terrestrial TV Broadcasting," IEEE Communications Magazine, vol. 33, pp. 100-109, February 1995.*

- An important feature of the SCT/FDE system proposed in these papers is that it employs a cyclic prefix as in OFDM systems.

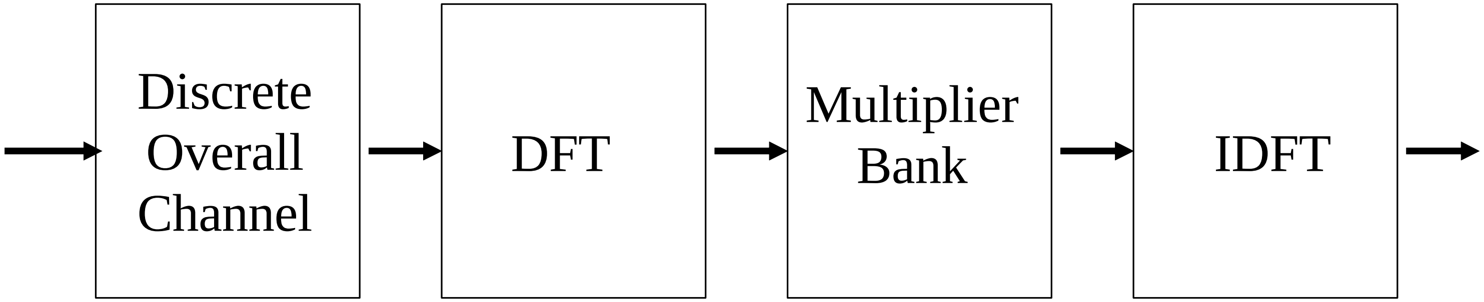
SCT/FDE (cont'd)

- SCT/FDE avoids the well-known problems of OFDM, which are its high peak-to-average power ratio (PAPR) and high sensitivity to the local oscillator phase noise.
- On channels with a short impulse response, there is a need neither for OFDM nor for SCT/FDE. Single-carrier transmission with time-domain equalization (SCT/TDE) is the right approach in this case. But SCT/TDE is not appropriate for long impulse response channels
- The articles published by this author in which SCT/FDE was shown to be an attractive alternative to OFDM led to the rebirth of frequency-domain equalization.

Schematics of OFDM and SCT/FDE



(a) OFDM



(b) SCT/FDE

OFDMA

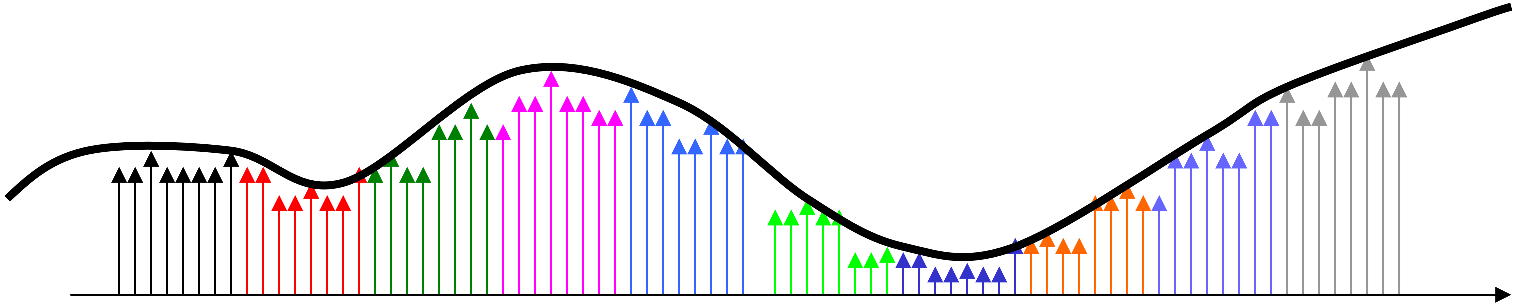
- In the IEEE 802.11a and HIPERLAN2 standards, OFDM is used with TDMA. In this scheme, a TDMA time slot is an integer multiple of an OFDM symbol.
- It is also possible to use OFDM with orthogonal frequency-division multiple access (OFDMA), where the N carriers are not all assigned to the same user.
- In OFDMA, the set of N carriers is partitioned into M subsets of N/M carriers, and resource assignment is performed subset by subset. This means that resources can be allocated to M users during the same OFDM symbol period.
- The word OFDMA was coined in a 1996 conference paper by this author in which this technique was proposed for the uplink in cable networks.

The Principle of OFDMA

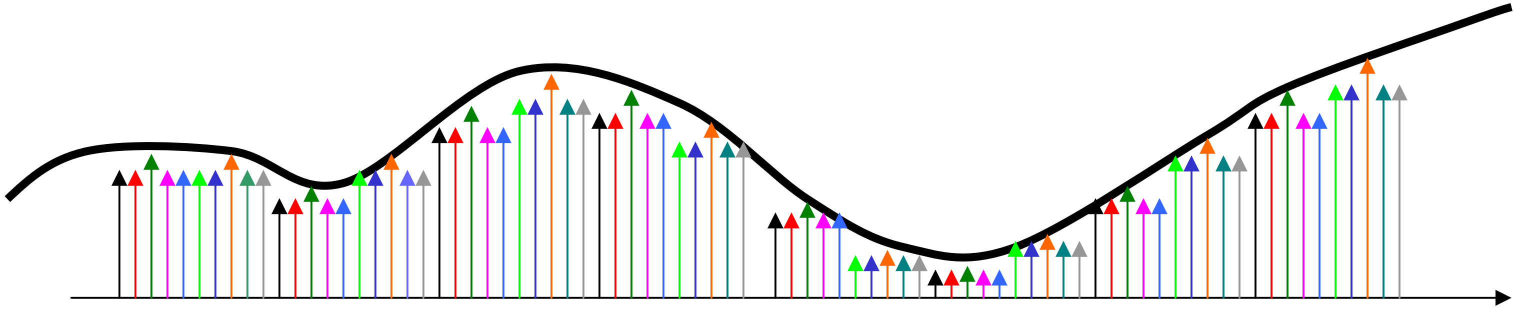
- OFDMA consists of assigning different carrier sets to different users. The simplest way to describe it is to assume that the number of carriers N is partitioned into M subsets of N/M carriers each and that each subset is assigned to a user.
- The carrier subset assigned to a user can be a cluster of carriers, a set of carriers uniformly distributed across the signal band, and the carriers can have fixed or dynamic allocation.
- In such an OFDMA system, M users can be served simultaneously by the base station, whereas a conventional OFDM/TDMA system (as in the IEEE 802.11 specifications) serves a single user during a given OFDM symbol.

Basic Variants of OFDMA

1. Clustered OFDMA



2. OFDMA with uniformly spaced carriers



Potential of OFDMA

- The first interesting feature of OFDMA compared to OFDM/ TDMA is that it reduces the granularity of the bursts allocated to different users, and this increases the efficiency of the Medium Access Control (MAC) Protocol.
- Another interesting feature is that OFDMA substantially increases the cell range on the uplink by concentrating the transmit power of the user terminal on a fraction of the total channel bandwidth.
- Indeed, with M carriers per group, the noise bandwidth is reduced by a factor of N/M. Assuming that the signal attenuation is proportional to the squared distance, OFDMA thus increases the cell range by a factor of 10.log(N/M).

Potential of OFDMA (cont'd)

- OFDMA can also increase the cell range on the downlink by allocating unequal signal powers to different sets of carriers and assigning them appropriately.
- Indeed, if a larger power is allocated to the sets assigned to distant users, the cell range will increase for a given total transmit power by the base station.
- Optimum power allocation consists of splitting the total power so as to receive the same power by all users. We assume here that all users request the same data rate and performance level.

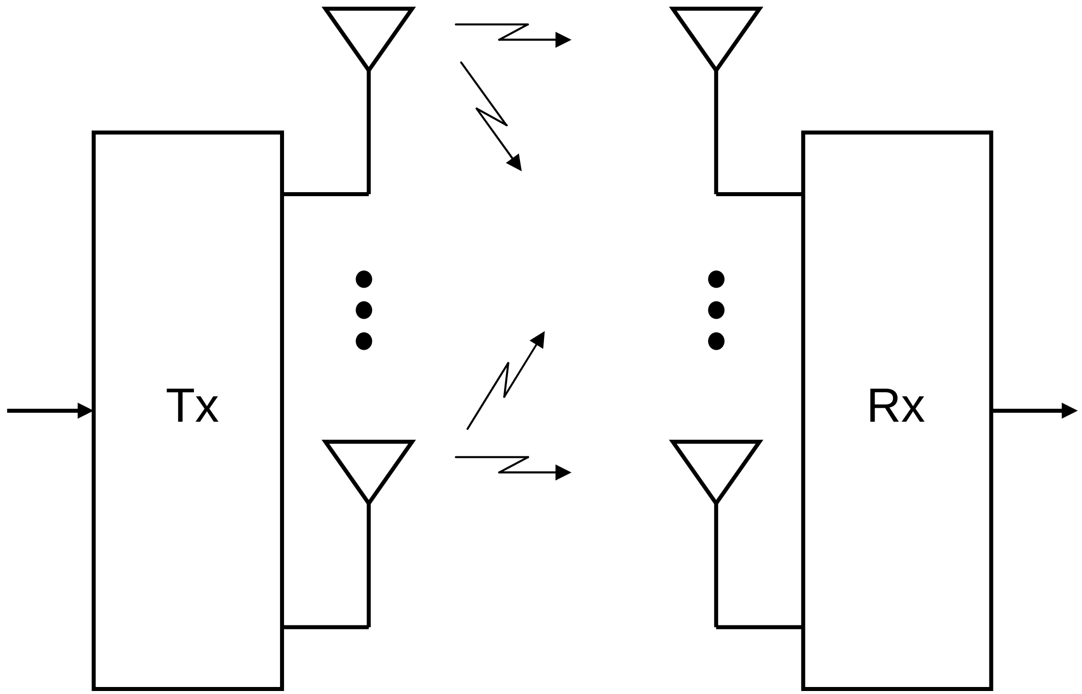
Diversity Issues in OFDMA

- Because it allocates only a portion of the channel to a given user, OFDMA suffers from a diversity loss compared to TDMA.
- The variant with carrier frequencies uniformly distributed over the channel bandwidth is more robust than the variant with clustered carriers.
- But in both cases, the symbols falling on faded frequencies will suffer and will be in error with a high probability. One way to overcome this problem is to protect these symbols using error correction coding.
- Two other techniques to recover the frequency diversity are precoding of input symbols and frequency hopping. The latter is used in the IEEE 802.16 specifications.

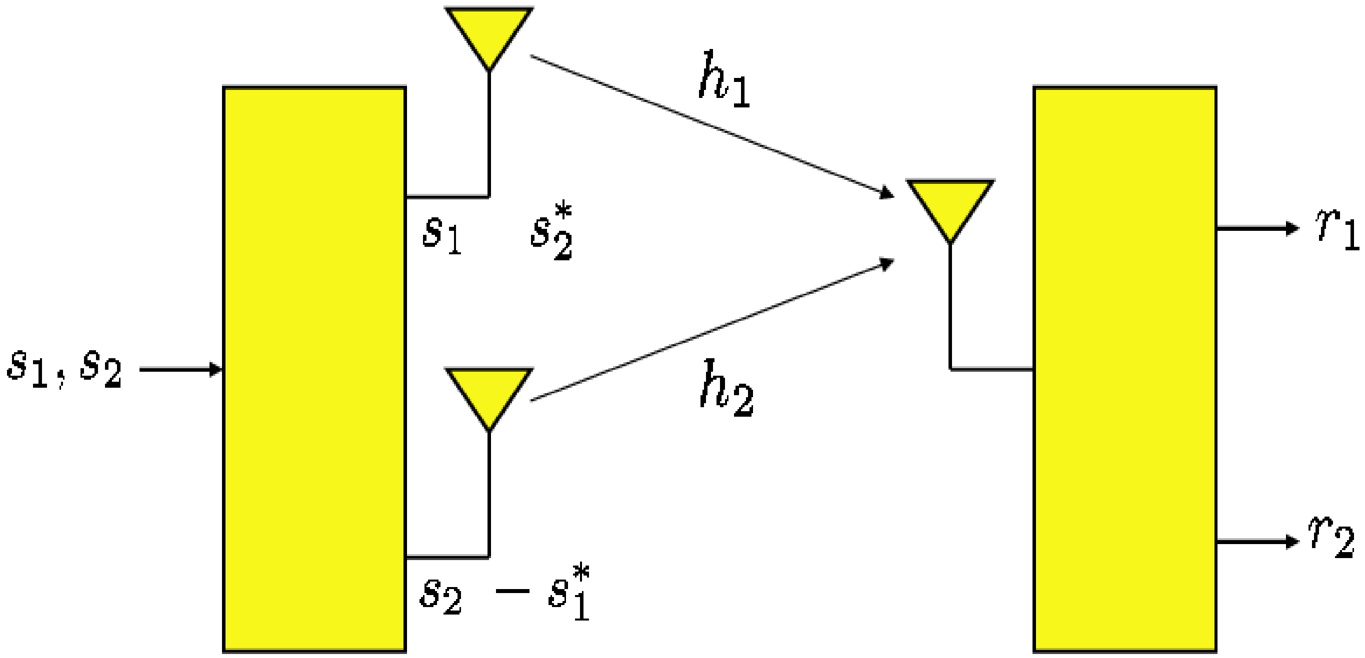
Fading and Spatial Diversity

- The PHY technologies used in the IEEE 802.16 specifications are robust against channel dispersion, but performance of BWA systems is also strongly affected by Rayleigh fading which is another characteristic of the channel.
- To compensate for fading, BWA wireless systems use spatial diversity, that is based on using multiple antennas at the transmitter and/or the receiver.
- When multiple antennas are used at both transmitter and receiver, the resulting system is called MIMO (Multiple input multiple output). In addition to diversity, MIMO systems can also increase cell throughput.
- WiMAX specifications define two mandatory MIMO profiles.

MIMO Schematic Block Diagram



Profile 1: Matrix A (Alamouti's STC)



Matrix A (cont'd)

- Denoting the channel response from Tx antenna 1 to the receiver by h_1 and its response from Tx antenna 2 to the receiver by h_2, the received signal samples at the two transmission instants are respectively given by:

$$r_1 = h_1 s_1 + h_2 s_2 + n_1$$

and

$$r_2 = h_1 s_2^* - h_2 s_1^* + n_2$$

where n_1 and n_2 are the additive noise terms affecting the two channels.

Matrix A (cont'd)

- The receiver computes the quantities:

$$x_1 = h_1^* r_1 - h_2 r_2^* = \left(|h_1|^2 + |h_2|^2\right) s_1 + h_1^* n_1 - h_2 n_2^*$$

and

$$x_2 = h_2^* r_1 + h_1 r_2^* = \left(|h_1|^2 + |h_2|^2\right) s_2 + h_2^* n_1 + h_1 n_2^*$$

- These expressions clearly show that symbols s_1 and s_2 can be recovered from x_1 and x_2 without any interference and that these estimations benefit from a perfect second-order diversity that is equivalent to receiver diversity based on maximum ratio combining (MRC).
- Alamouti's STC can also be combined with MRC, and the resulting 2x2 system benefits from fourth-order diversity.

Profile 2: Spatial Multiplexing

- The second multiple antenna profile included in the IEEE 802.16e specifications is the 2x2 MIMO technique based on the so-called matrix $B = (s_1, s_2)^T$.
- This system performs pure spatial multiplexing and does not benefit from any diversity on the transmitter side. But it does offer a second-order diversity on the receiver side when detected using maximum-likelihood (ML) detection.
- To describe this technique, we omit the time and frequency dimensions leaving only the space dimension. The symbols transmitted in parallel by transmit antenna 1 and transmit antenna 2 are denoted s_1 and s_2, respectively.

Spatial Multiplexing (cont'd)

- Denoting by h_{ji} the channel response from transmitter i to receiver j, the signals received by the two receiver antennas are given by:

$$r_1 = h_{11} s_1 + h_{12} s_2 + n_1$$

and

$$r_2 = h_{21} s_1 + h_{22} s_2 + n_2$$

- These two equations can be combined and written in matrix form as:

$$\begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix}$$

Optimum Detection

- The ML detector makes an exhaustive search over all possible values of the transmitted symbols and decides in favor of (s_1, s_2) which minimizes the Euclidean distance:

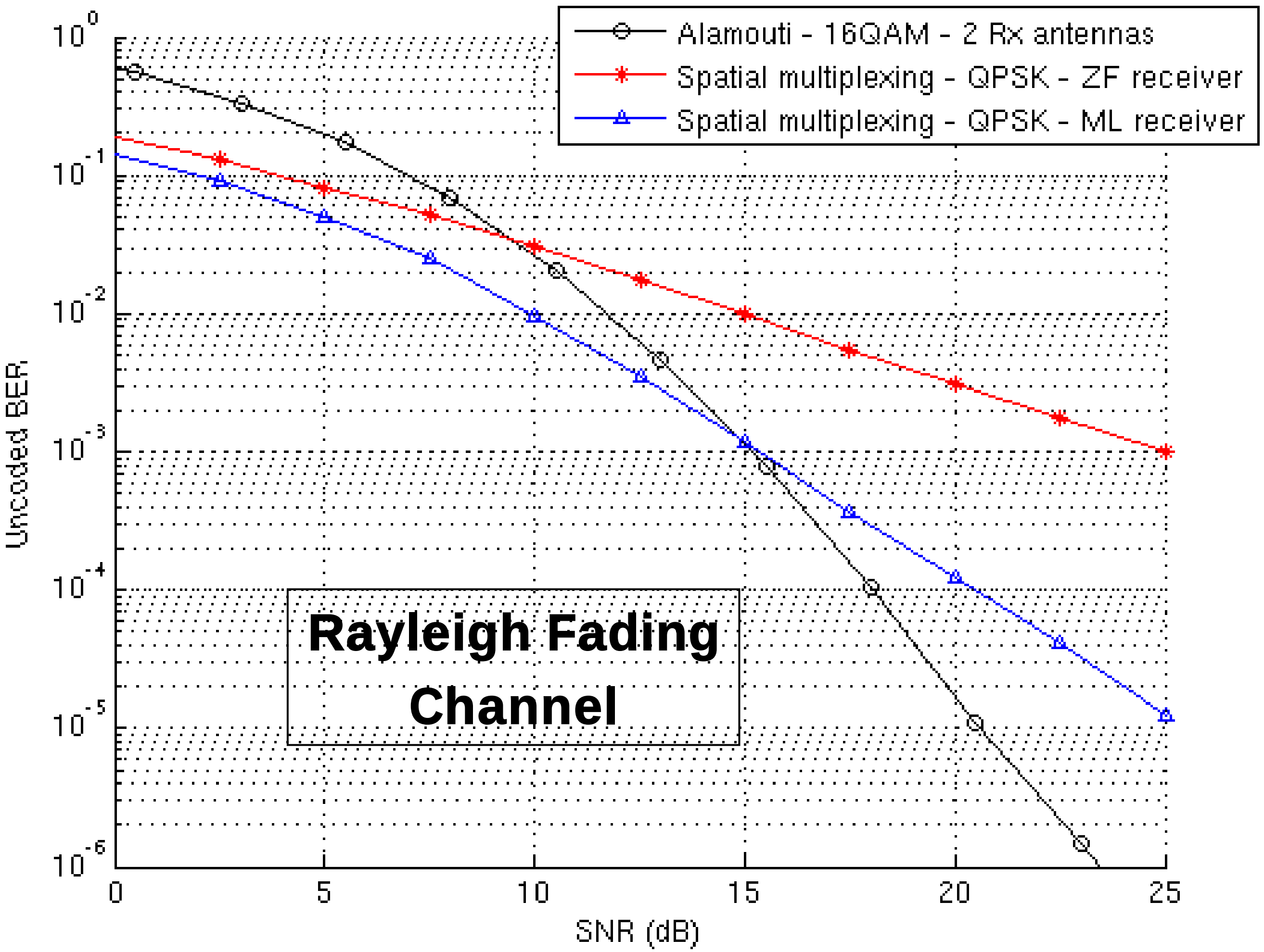
$$D\left(s_1, s_2\right) = \left\{ \left| r_1 - h_{11} s_1 - h_{12} s_2 \right|^2 + \left| r_2 - h_{21} s_1 - h_{22} s_2 \right|^2 \right\}$$

- The complexity of the ML detector grows quadratically with the size of the signal constellation, and this motivates the use of simpler suboptimum receivers in practical implementations.
- Indeed, with the largest signal constellation (64-QAM) included in the IEEE 802.16e specifications, the complexity is proportional to $64^2 = 4096$, which is clearly prohibitive.

Comparison of MIMO Options

- Since the 2x2 spatial multiplexing (SM) technique has only a 2nd-order diversity and Alamouti's STC has a 4th-order diversity when combined with MRC, the latter technique can be expected to have better bit error rate (BER) performance.
- But spatial multiplexing offers a doubled bit rate when it uses the same modulation scheme as the Alamouti/MRC system.
- To make an objective and meaningful comparison between the two MIMO profiles, we need to use them at the same spectral efficiency rather than with the same modulation.
- Note that the Alamouti/MRC system with a modulation transmitting 2m bits per symbol has the same spectral efficiency as the 2x2 Spatial Multiplexing system with a modulation transmitting m bits per symbol.

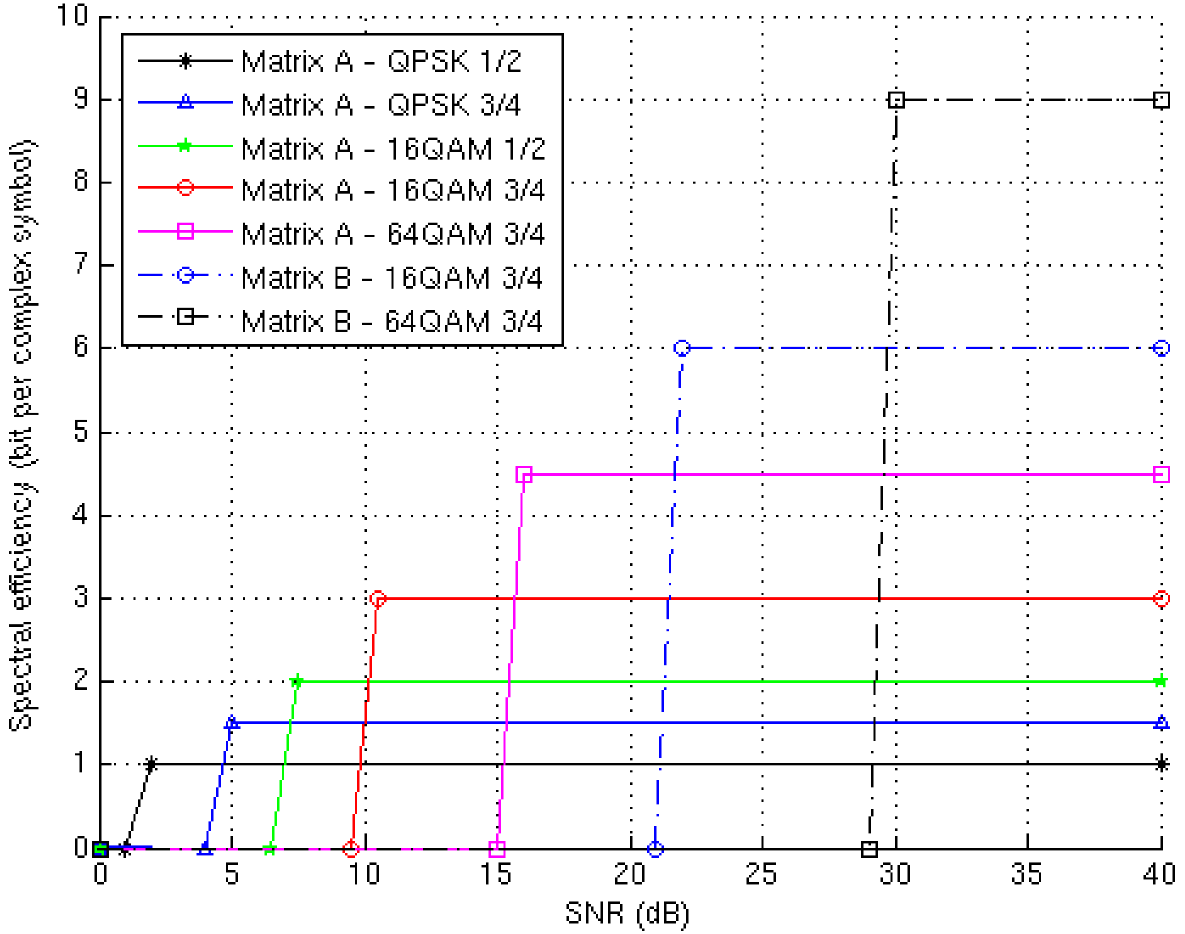
Alamouti / MRC vs. Spatial Multiplexing



MIMO Link Adaptation

- The BER results in the previous figure suggest that the MIMO option to be used is a function of the channel SNR and the throughput required.
- In single-antenna systems, the throughput is optimized through link adaptation, which selects a signal constellation and a code rate as a function of the channel.
- This concept, called adaptive modulation and coding (AMC), must be extended to the space dimension in multi-antenna systems to make the best use of available MIMO options.
- We now illustrate MIMO link adaptation for the ITU Pedestrian Channel A corresponding to a speed of 3 km/hour.

AMC for MIMO Systems



Summary and Conclusions

- We have given an overview of BWA systems, highlighted the propagation problems that are specific to these systems and described the basic physical layer technologies adopted in the IEEE 802.16 and IEEE 802.16e specifications.
- The OFDM- and OFDMA-based physical layers adopted for WiMAX systems are capable of compensating for large channel dispersions. Also, the MIMO profiles included in the specifications provide spatial diversity on one hand and increase cell capacity on the other hand.
- With the advanced OFDMA and MIMO technologies adopted, WiMAX systems are today in a good position in the competition for tomorrow's 4G networks.