Chapter 15 Antennas for mobile systems

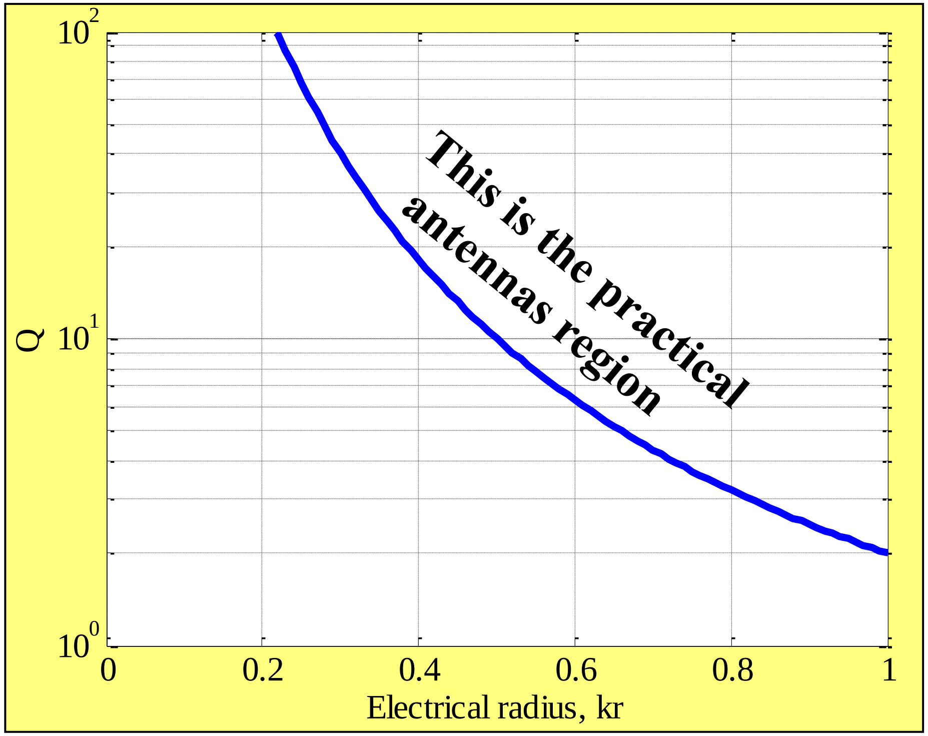
- Mobile terminal antennas
  - Small antennas fundamentals
  - Dipoles
  - Patches
  - Human body interaction
- Base station antennas
  - Antennas for macrocells
  - Microcell antennas
  - Picocell antennas
  - Antennas for WLAN

Small antennas characteristics

- Small mobile phones or other small user equipment also mean small antennas
- Omni-directional azimuth radiation pattern and wide beam width in the vertical direction
- Radiated field strength is proportional with the integral of the current: larger current gives stronger field and the smaller the antenna is the larger the current must be to achieve the same field strength
- Large current is achieved in the antenna if the antenna is in resonance with the frequency used, but with reduced bandwidth as a result also

Small antenna definition

- Electrically small if antenna can be contained in a sphere of radius *r* such that $kr < 1$, $k=2\pi/\lambda$ (*k* is the wave number). Trade-off size, bandwidth and directivity
- Increasing bandwidth tends to decrease efficiency. Bandwidth and directivity cannot both be increased if antenna kept small. As size decreases radiation resistance decreases relative to ohmic loss, thus reduced efficiency
- Examine the quality factor *Q* (unloaded) defined as $Q = f_0/\Delta f_{3dB}$. Unloaded *Q* modelled $Q=1/(kr)^3+1/kr$



A more broadband antenna means a lower *Q* factor

Increasing bandwidth using two dipole antennas

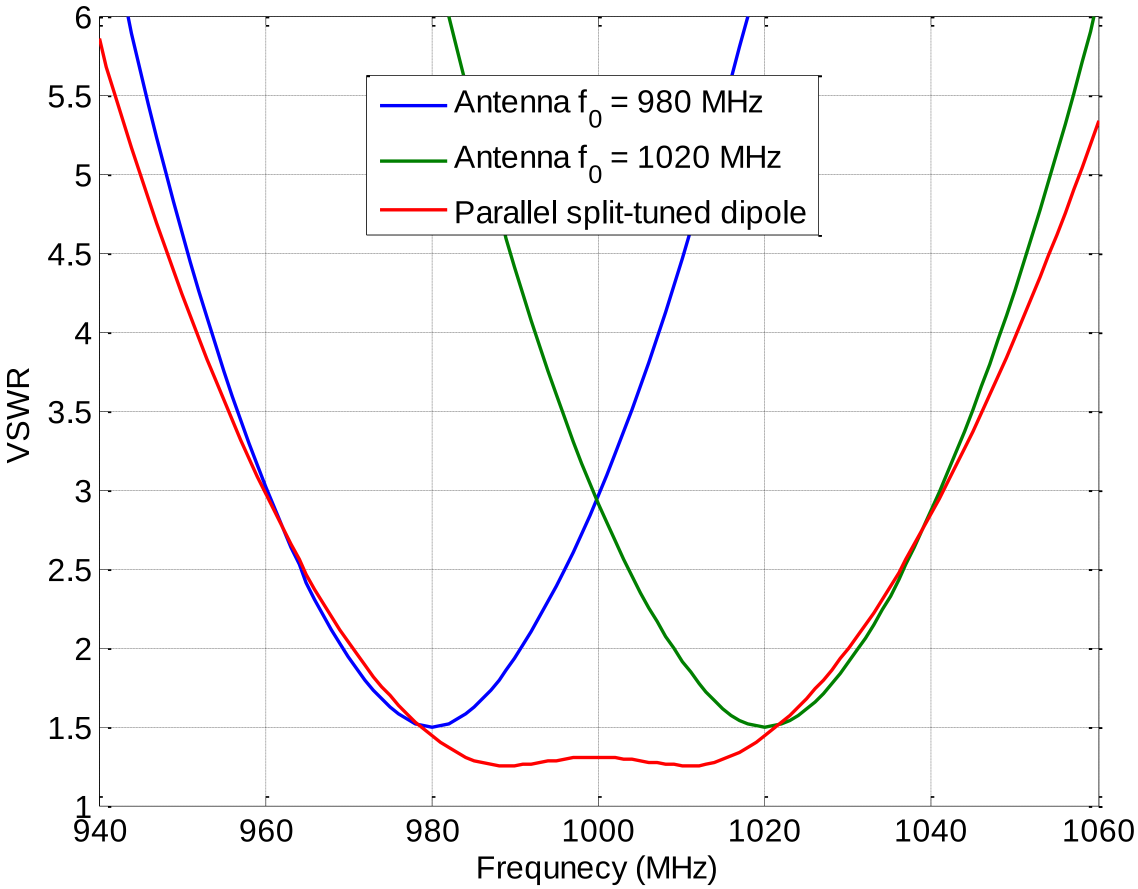
$$Z_a = R + j\left(\omega L - \frac{1}{RC}\right)$$

$$= R\left(1 + jQ\left(\frac{f}{f_0} - \frac{f_0}{f}\right)\right)$$

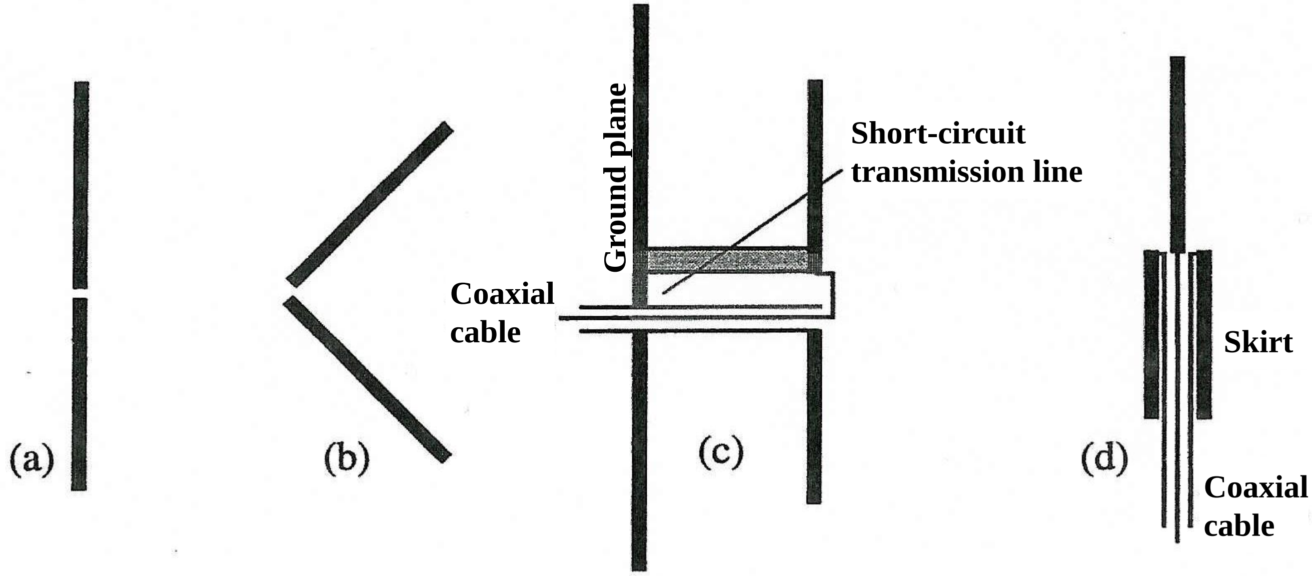
$$\rho = \frac{V_r}{V_i} = \frac{Z_a - Z_s}{Z_a + Z_s}$$

$$VSWR = \frac{1+|\rho|}{1-|\rho|}$$

$Z_s = 50\ \Omega$
Q chosen = 21.5
VSWR
Voltage standing wave ratio

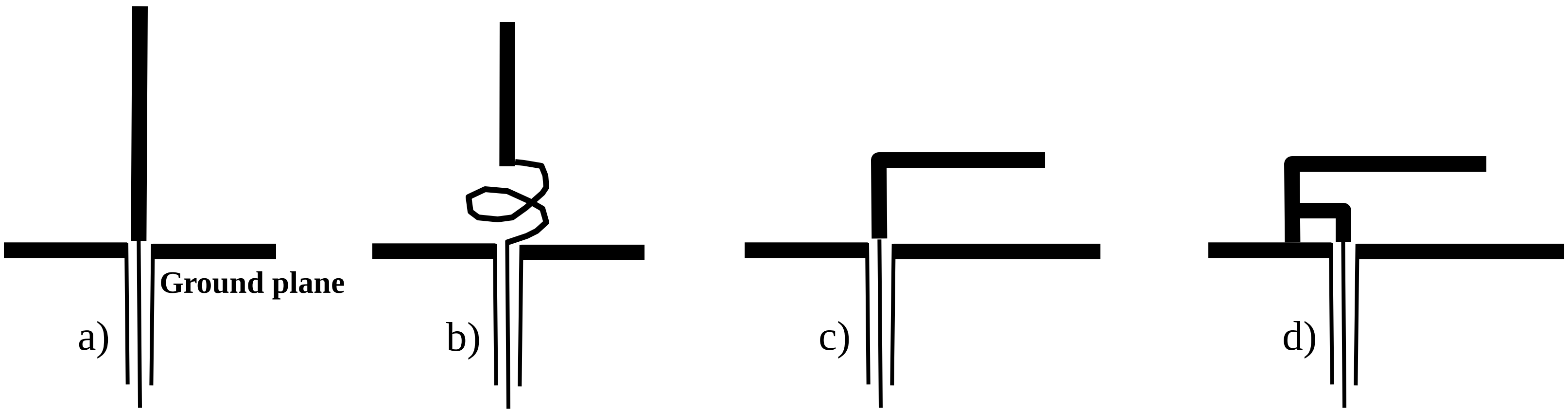


Various dipole antennas



a) Ideal dipole antenna
b) V-form to give stronger radiation in the direction the opening of the V and less backwards
c) Practical realisation taking mechanical fastening and feed with coaxial cable through the ground plane. On arm of the dipole is connected to the cable case, the other inner conductor and a pipe connected to the ground plane. The pipe and the cable case become a short-circuit transmission line in parallel to the antenna impedance. The result is a well matched dipole antenna that is shorter than a half wave length
d) Feed with coaxial cable from one end where one dipole arm is the extension of the inner conductor and the other a cylindrical skirt surrounding the cable and connected with the case of the cable

Monopole with some alternative designs



a) Idealist monopole whip antenna. Removing one branch form the dipole antenna and replacing with a ground plane it becomes a monopole antenna half the length that of the dipole antenna. It is easy to feed

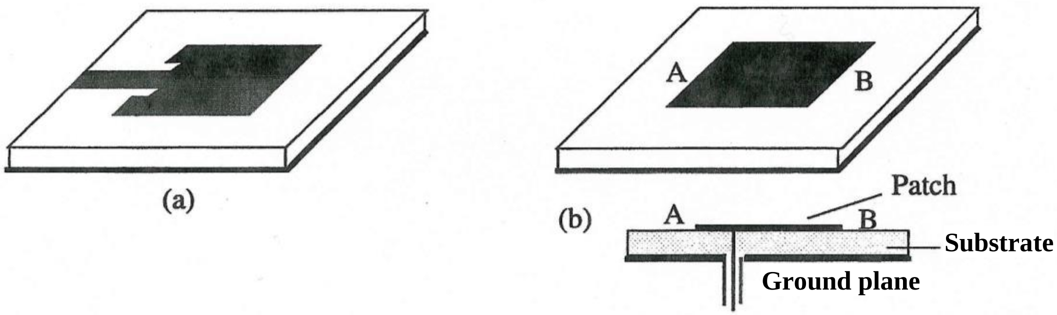
b) Traditional mobile phone antenna. A monopole shorter than $\lambda/4$ gets unwanted capacitive input impedance. This is compensated by using a coil near the feed point

c) Inverted L-antenna. Close to the ground plane. Problem with small resonance

d) Inverted F-antenna. Increased input impedance and resonance

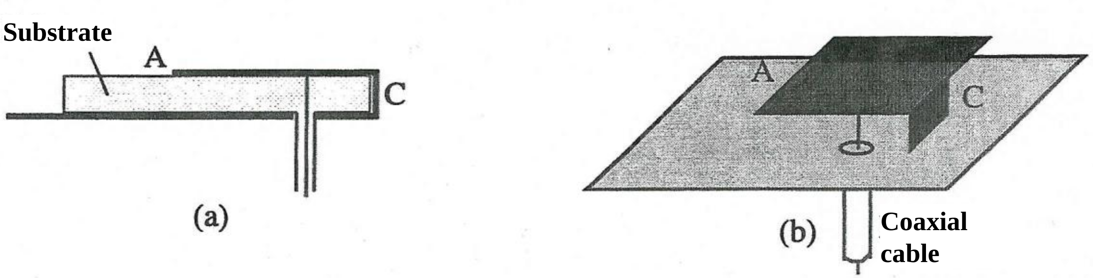
Patch antenna

Example: micro strip antenna, printed metal pattern on a dielectric substrate.



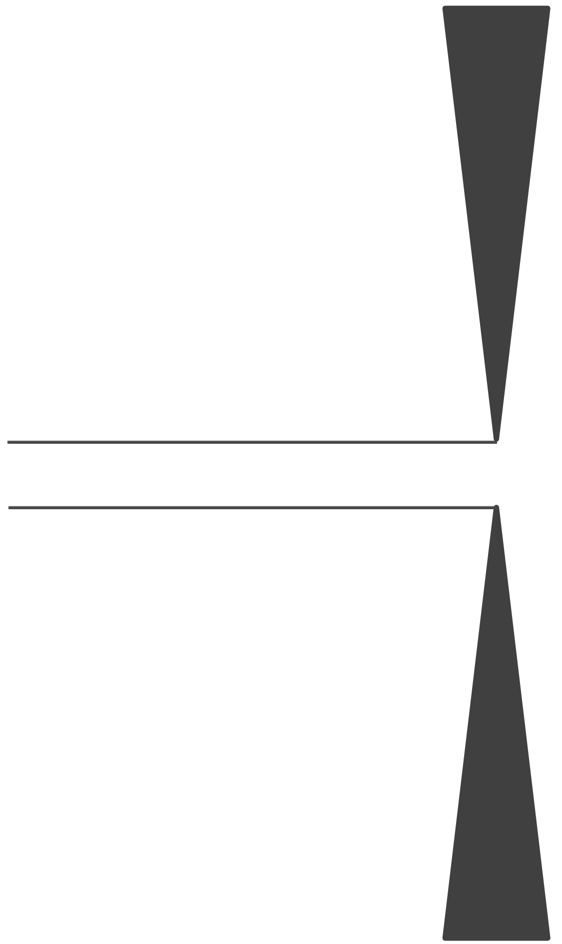
a) Feed using a transmission line
b) Feeding with coaxial cable through a ground plane

The current flows from edge A to B, maximum in the middle and zero at the edge. Radiation from the edges. The centre frequency determined by substrate permittivity and distance between A and B. This distance is close to λ/2 in substrate.



a) Short-circuit patch gives a smaller antenna, men the same field
b) Inverted F without a substrate and only partly short-circuit

Wideband dipole



Specific absorption rate (SAR)

- Some focus on potential health effects when using mobile phones
- For this frequency range the radiation is referred to as non-ionising, i.e., not radioactive radiation
- Interaction between non-ionising effects and human tissue is heating (but other views have been expressed)
- As a precautionary measure regulatory bodies issue limits

Specific absorption rate (SAR)

- Non-ionising radiation
- Given a current density ***J*** and an electric field ***E*** the power absorbed P_V per unit volume human tissue with conductivity σ (Ω^{-1}m^{-1}) is

$$P_V = \frac{1}{2}\mathbf{J}\cdot\mathbf{E}^* = \frac{1}{2}\sigma|\mathbf{E}|^2 \quad (\mathrm{W/m^3})$$

- Introducing tissue density ρ (kg/m^3), the absorption per unit mass is

$$P_g = \frac{1}{2}\frac{\sigma}{\rho}|\mathbf{E}|^2 \quad (\mathrm{W/kg}) \qquad P = \int_M P_g\,dm$$

- P_g is the specific absorption rate (SAR) and P the power absorbed given mass M

Tissue dielectric properties

Tissue	Permittivity (ε)	Conductivity (σ)
Bladder	18.93	0.38
Fat (Mean)	11.33	1.1
Heart	59.89	1.23
Kidney	58.68	1.39
Skin (dry)	41.4	0.87
Skin (wet)	46.08	0.84
Muscle (parallel fibre)	56.88	0.99
Muscle (transverse fibre)	55.03	0.94
Cerebellum	49.44	1.26
Breast fat	5.42	0.04
Average brain	45.8	0.77
Average skull	16.62	0.24
Average muscle	55.95	0.97

SAR regulations

- SAR exposure limits have been issued by international organisations
- International committee on non-ionising radiation protection (ICNIRP), Institute of electrical and electronics engineers (IEEE) issued SAR values for the whole body, the head and other parts
- Regulations of far-field strength (V/m), e.g., from Nkom, Norway, based on ICNIRP

  WLAN (2.4 GHz) and 0.1 W EIRP: limit 61 V/m

  UMTS (2 GHz) and 416 W EIRP: limit 61 V/m, happens at <2 m from transmitter

  TV (200 MHz) and 100 kW EIRP: limit 28 V/m happens at 62 m from transmitter

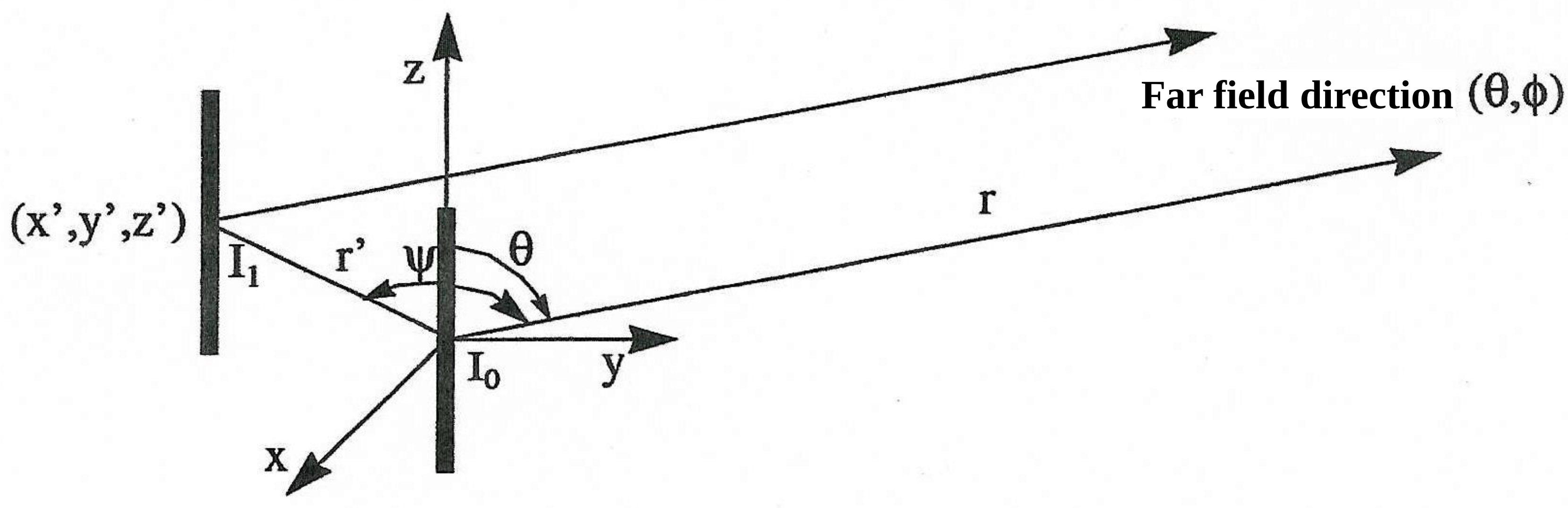
Base station antennas

- Base station provide coverage in azimuth and provide directivity in the vertical plane
- Use a vertical array of antennas
- Limit azimuth to sectors

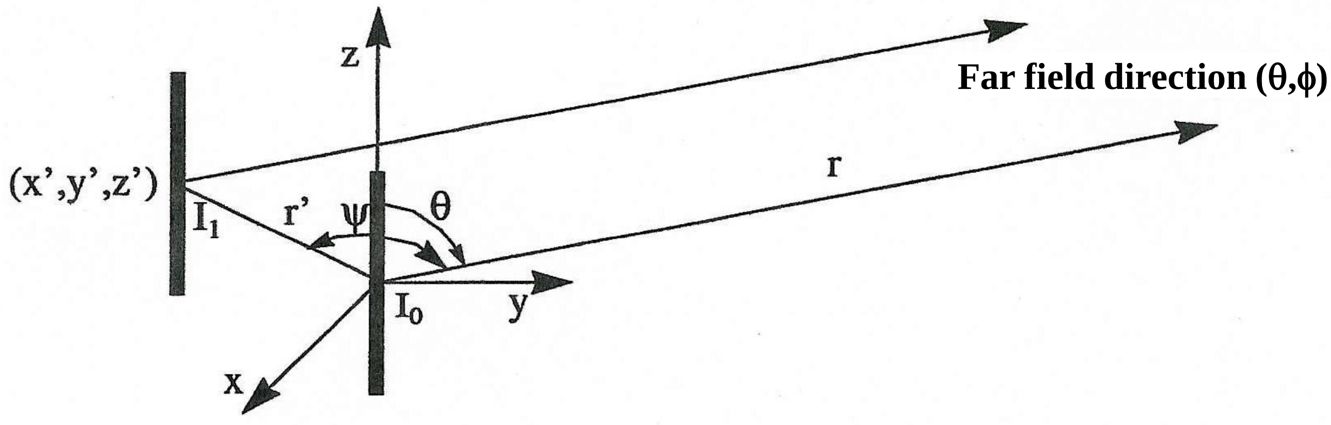
Phased array (dipole) antennas

With single antennas arranged in a group or array new radiation patterns can be formed. For example improve directivity, steerable beam, or nulls in the direction for unwanted signals. Very interesting for radar applications, smart adaptive antennas for mobile base stations, multiple-input-multiple-output (MIMO) systems.

The example below shows an array with two half-wave dipoles



Far field from an array antenna with 2 dipoles



Far field as previously for one half-wave dipole, $L=\lambda/2$:

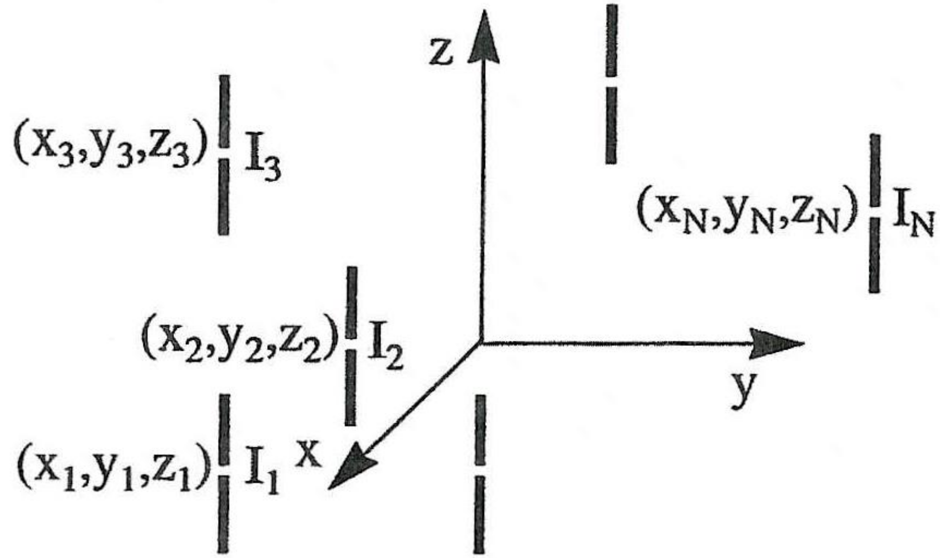
$$E_\theta = Z_0 H_\phi = j\frac{Z_0}{2\pi} I_0 \frac{e^{-jk_0 r}}{r} \frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta}$$

From the second with the feed current I_1, and changed distance for the phase:

$$r - r'\cos\psi = r - \left(x'\sin\phi + y'\sin\phi\right)\sin\theta + z'\cos\theta$$

$$E_\theta = Z_0 H_\phi = j\frac{Z_0}{2\pi} I_1 \frac{e^{-jk_0 r}}{r} \frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta} e^{jk_0\left(\left(x'\sin\phi + y'\sin\phi\right)\sin\theta + z'\cos\theta\right)}$$

Far field from an array antenna with many dipoles



The far field is found by superposition of all *N* antennas in the array:

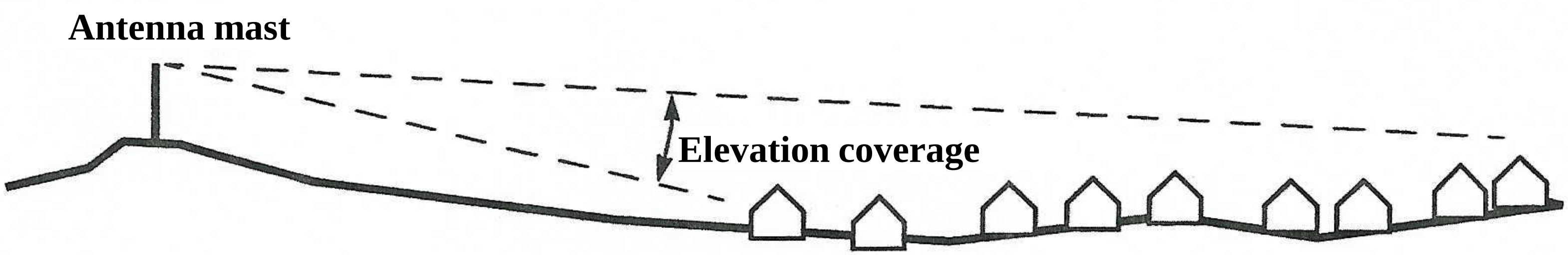
$$E_\theta = Z_0 H_\phi = j\frac{Z_0}{2\pi}\frac{e^{-jk_0 r}}{r}\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta}\sum_{n=1}^{N} I_n e^{jk_0((x_n\sin\phi + y_n\sin\phi)\sin\theta + z_n\cos\theta)}$$

$$= g'(\theta)F(\theta,\phi)\frac{e^{-jk_0 r}}{r}$$

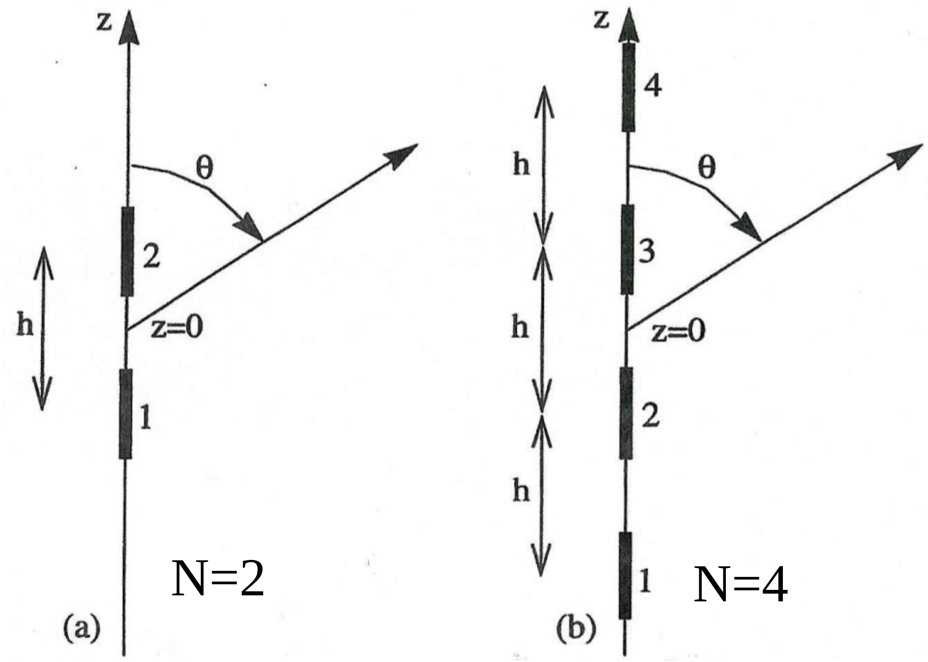
where $g'(\theta) = j\frac{Z_0}{2\pi}\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta}$ and $F(\theta,\phi) = \sum_{n=1}^{N} I_n e^{jk_0((x_n\sin\phi + y_n\sin\phi)\sin\theta + z_n\cos\theta)}$

$g'(\theta)$ is the element factor, the normalised far field for one antenna
$F(\theta,\phi)$ is the array factor only dependent on the positions and feed current amplitudes

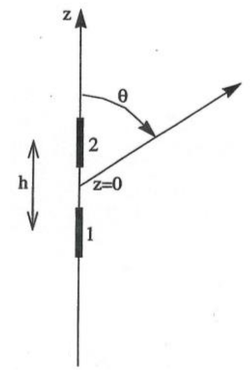
Modify radiation patterns in the vertical plane



Possible by mounting one dipole above the other



Vertical array



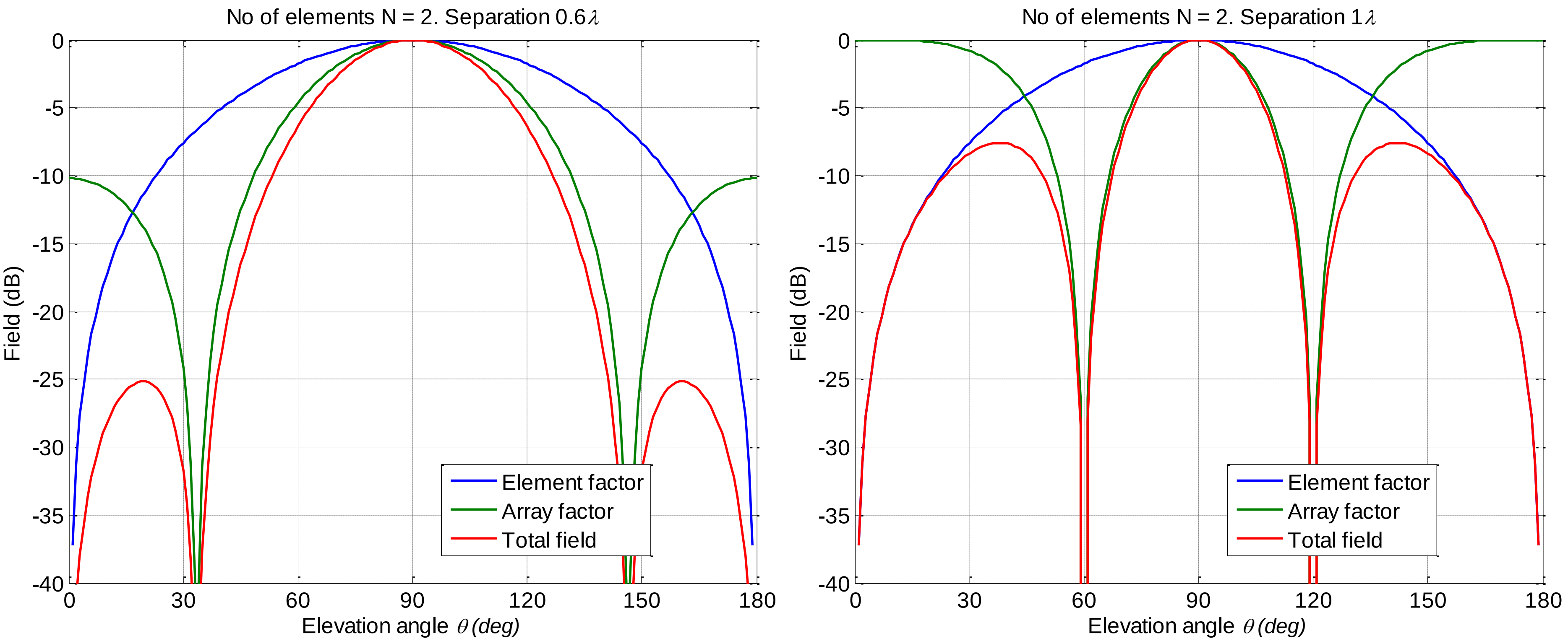
Vertical array simplifies as x_n and y_n become zero.
For N = 2 separated by h and z=0:

$$F_2(\theta) = I_0\left[e^{jk_0\left(\frac{-h}{2}\cos\theta\right)} + e^{jk_0\left(\frac{h}{2}\cos\theta\right)}\right]$$
$$= I_0\left[\cos\left(k_0\left(\frac{-h}{2}\cos\theta\right)\right) + j\sin\left(k_0\left(\frac{-h}{2}\cos\theta\right)\right) + \cos\left(k_0\left(\frac{h}{2}\cos\theta\right)\right) + j\sin\left(k_0\left(\frac{h}{2}\cos\theta\right)\right)\right]$$
$$= 2I_0\cos\left(k_0\left(\frac{h}{2}\cos\theta\right)\right)$$

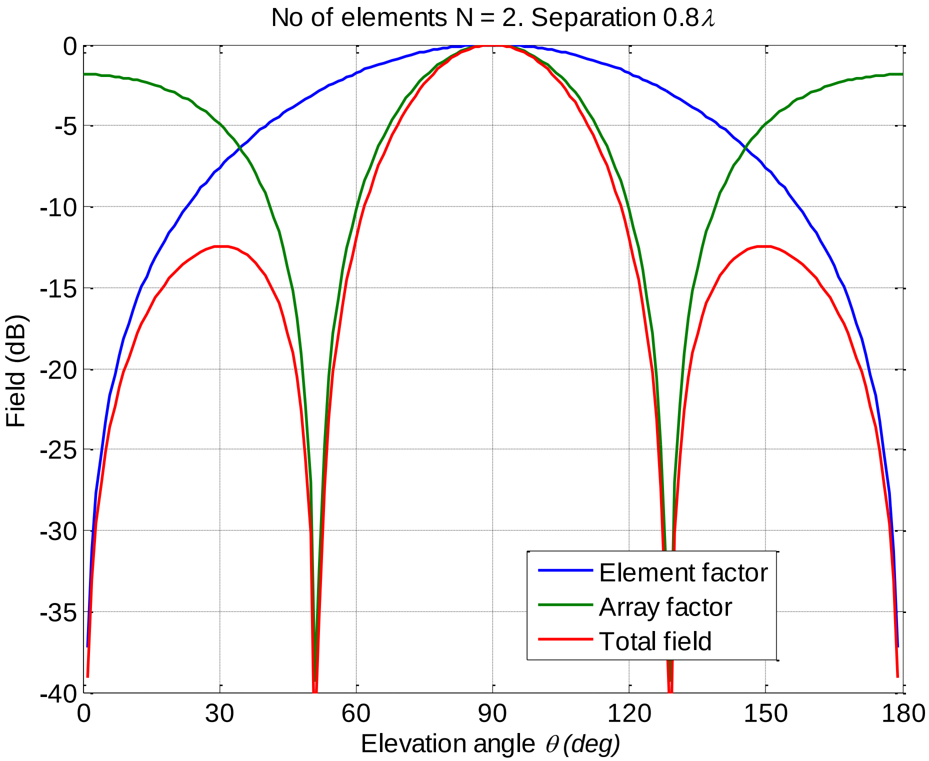
In general for even number N:

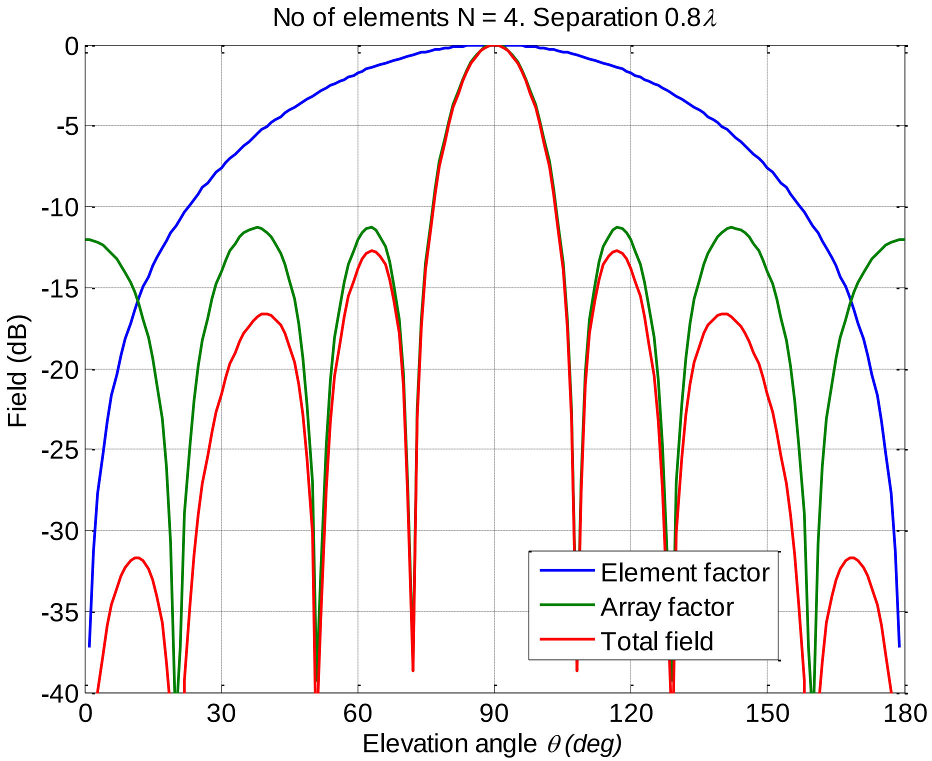
$$F_N(\theta) = 2I_0\left[\cos\left(k_0\left(\frac{-h}{2}\cos\theta\right)\right) + \cos\left(k_0\left(\frac{3h}{2}\cos\theta\right)\right) + \ldots + \cos\left(k_0\left(\frac{(N-1)h}{2}\cos\theta\right)\right)\right]$$

Vertical array 2 elements, different separation



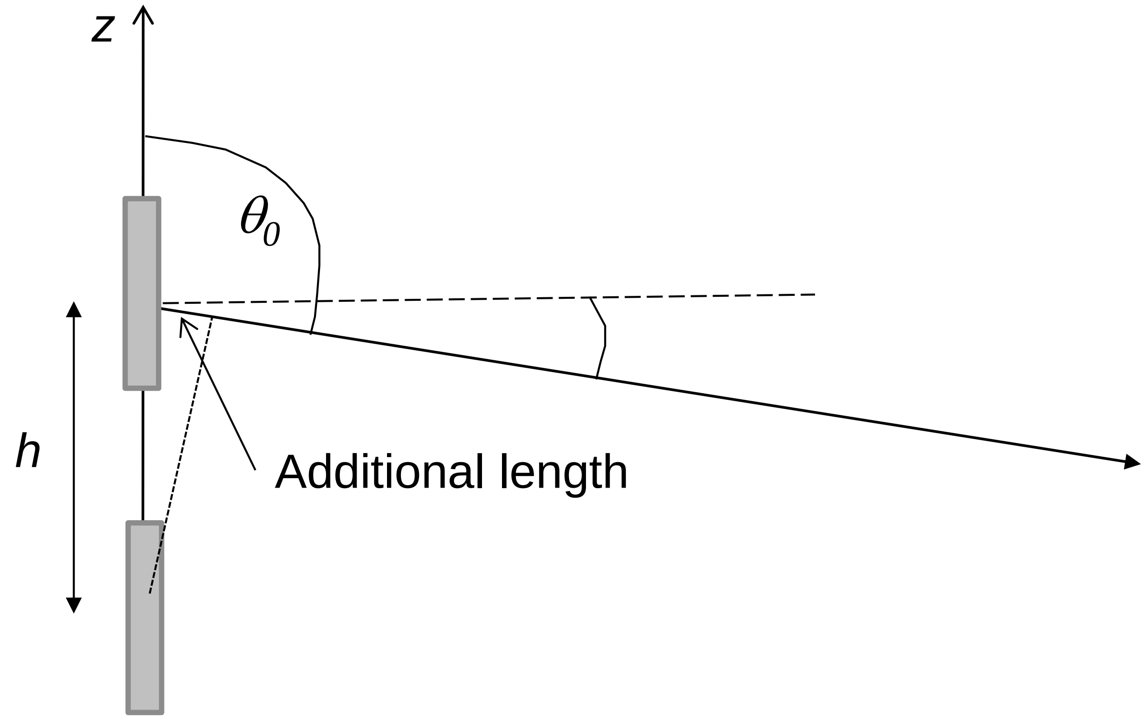
Vertical array same separation different number of elements





Down tilt

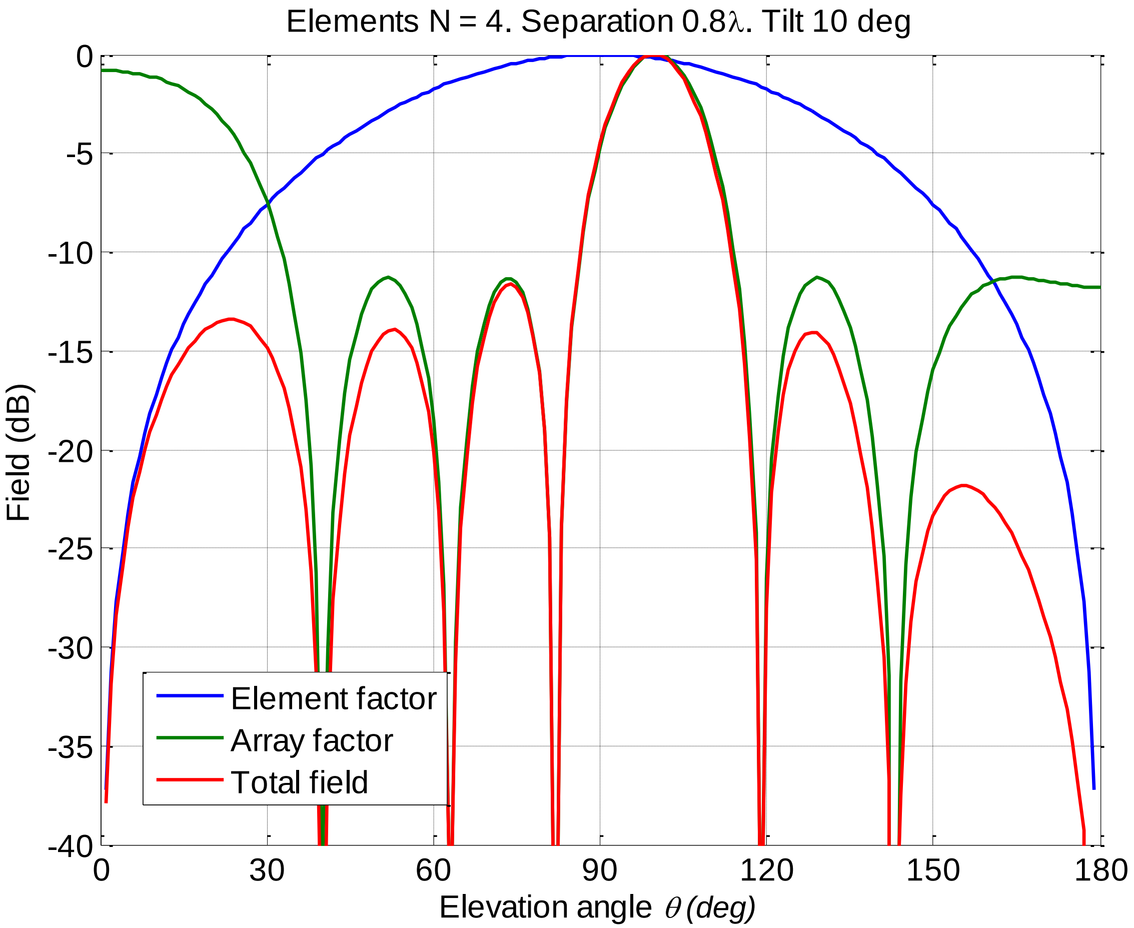
Down tilt possible by controlling the phase



For N = 2:

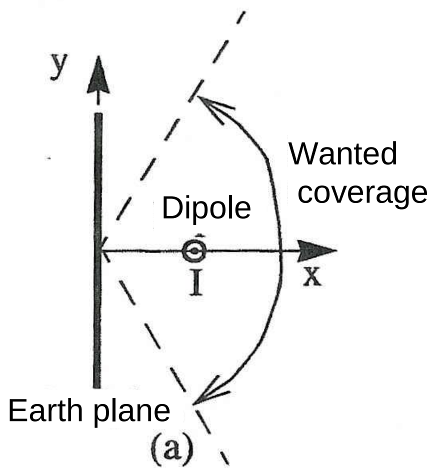
$$F_2(\theta) = 2I_0 \cos\left(k_0\left(\tfrac{h}{2}\left(\cos\theta - \cos(\theta_0)\right)\right)\right)$$

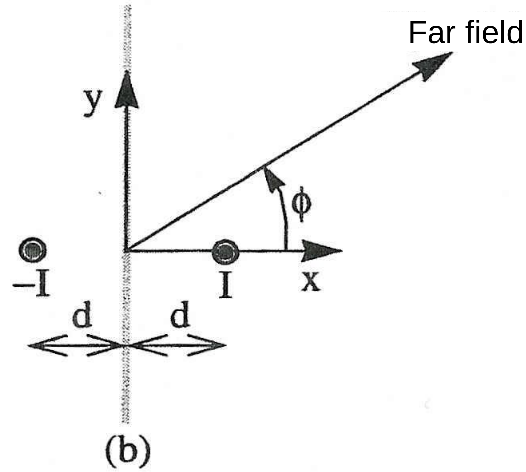
Four elements with downtilt



Modifying the radiation pattern in the horzontal plane

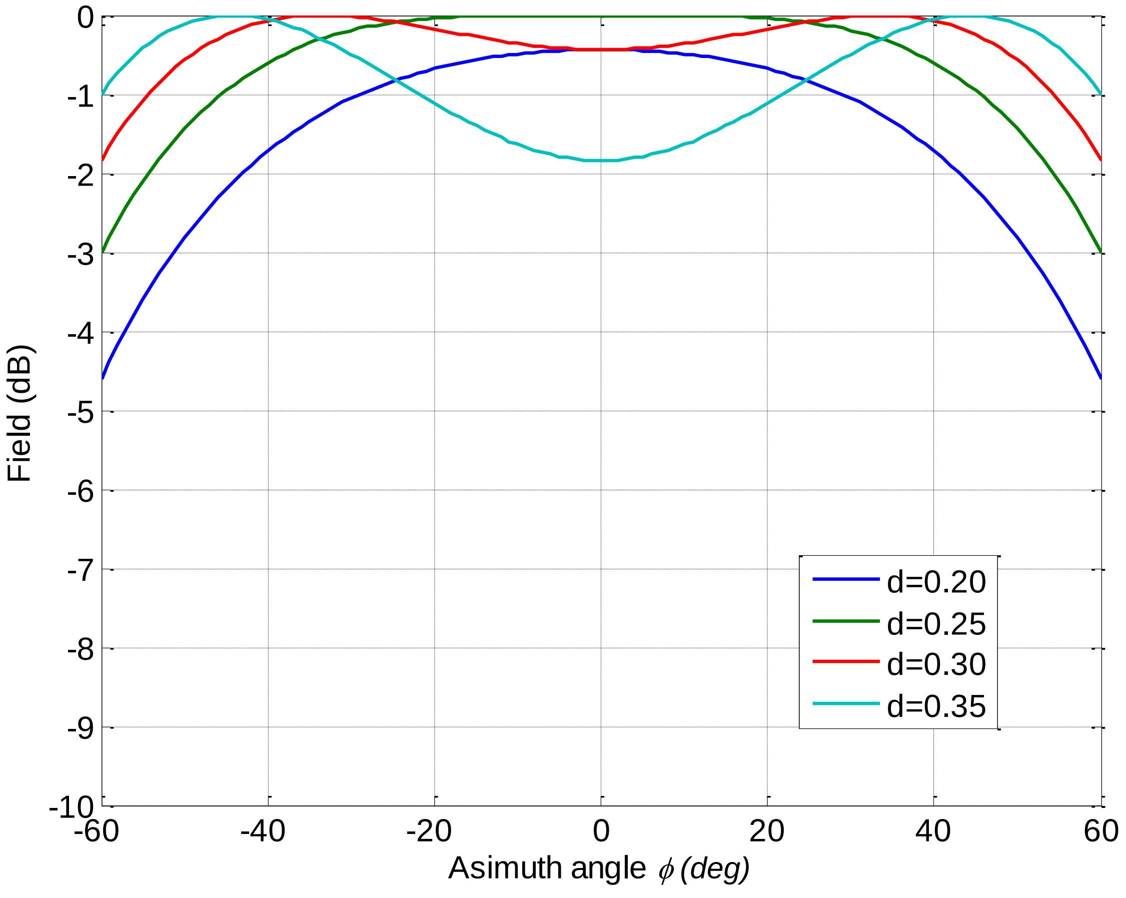
Dipoles have omnidirectional radiation pattern. A mobile base station may need to cover just a sector. Can be achieved using an Earth-plane behind the dipole.





$$F(\theta) = Ie^{jk_0 d\cos\phi} + (-I)e^{jk_0(-d)\cos\phi}$$
$$= 2I\sin(k_0 d\cos\theta)$$

Horizontal sectors



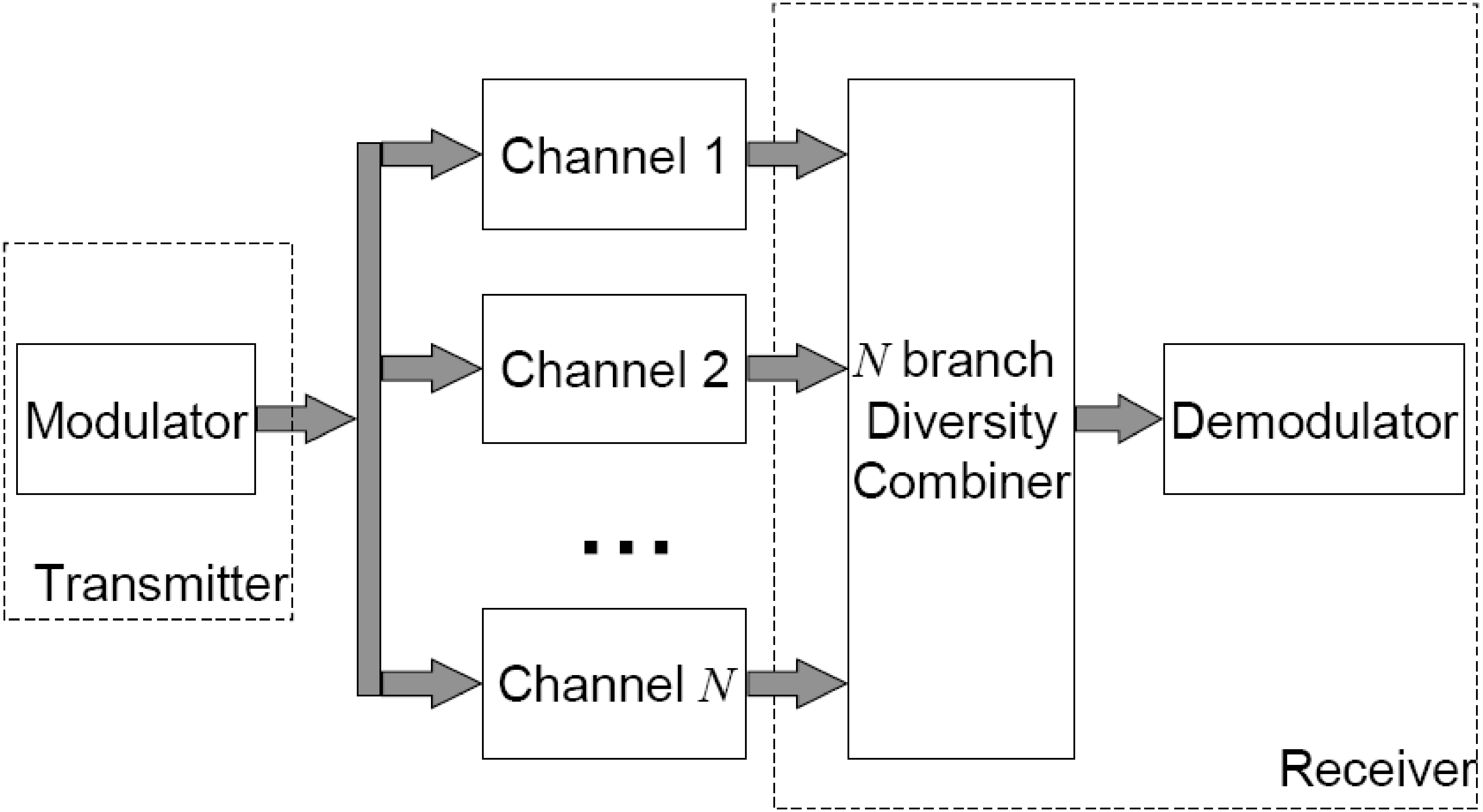
Chapter 16 Overcoming narrowband fading via diversity

Impairment	Remedy
Narrowband fast fading	Diversity
Wideband fading	Equaliser
Co-channel interference	Adaptive antennas

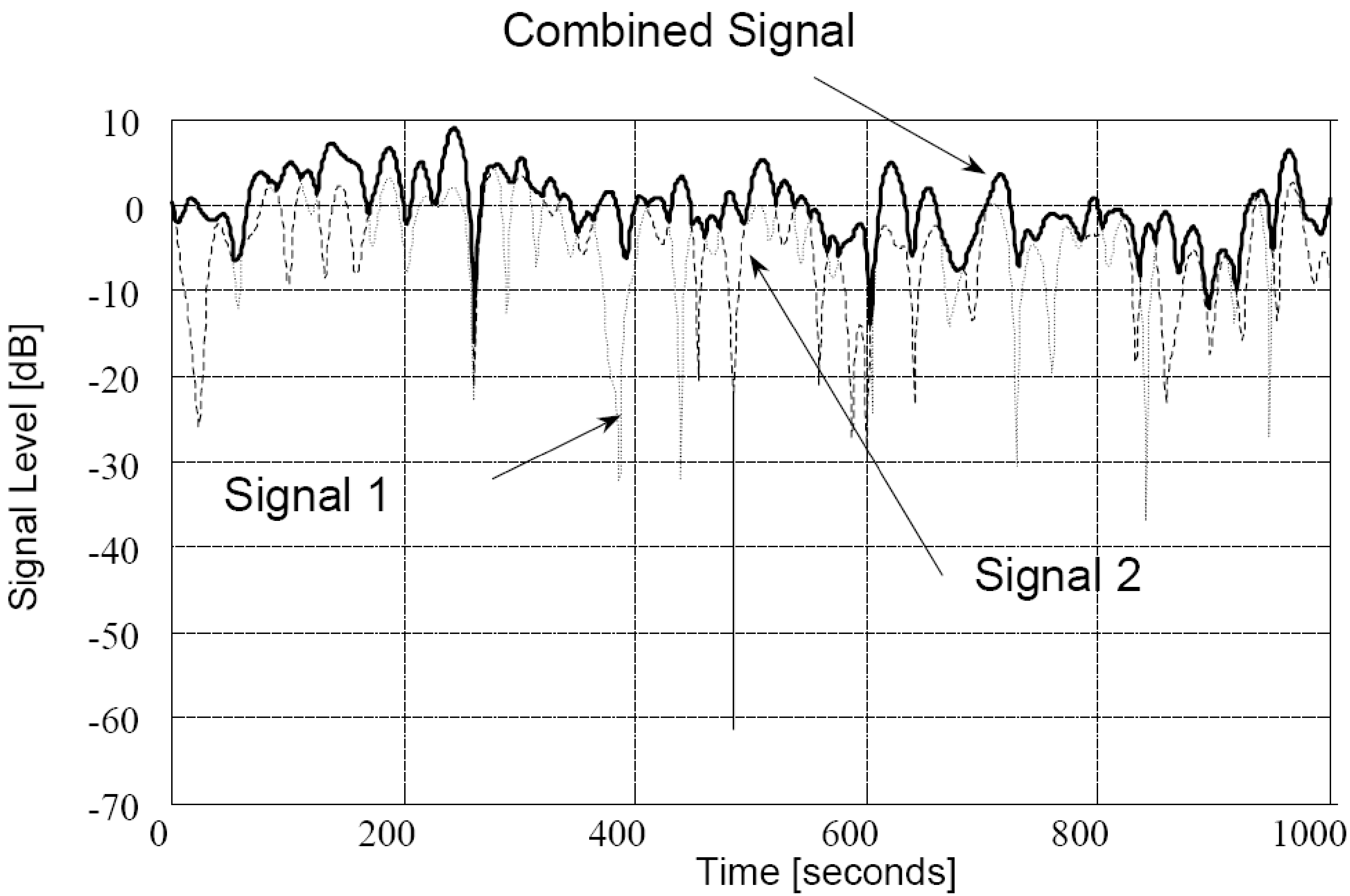
Diversity

- Aim: Reduce effects of fast fading
- Concept:
  - Multiple branches, independent fading
  - Process branches to reduce fading probability
- If probability of a deep fade on one channel is p, probability on N channels p^N
- Example: 10 % chance of losing contact for one channel becomes $0.1^3 = 0.001 = 0.1\%$ with 3 channels

Generic combining architecture



Select largest signal



Requirements to get diversity improvement

- Combination of several signals
- Signal not much correlated
- Correlation definition, channels α_1 and α_2

$$\rho_{12} = \frac{E\left[(\alpha_1 - \mu_1)(\alpha_2 - \mu_2)^*\right]}{\sigma_1 \sigma_2} \quad \text{for Rayleigh} \quad \rho_{12} = \frac{E\left[\alpha_1 \alpha_2^*\right]}{\sigma_1 \sigma_2}$$

- Similar power approximately

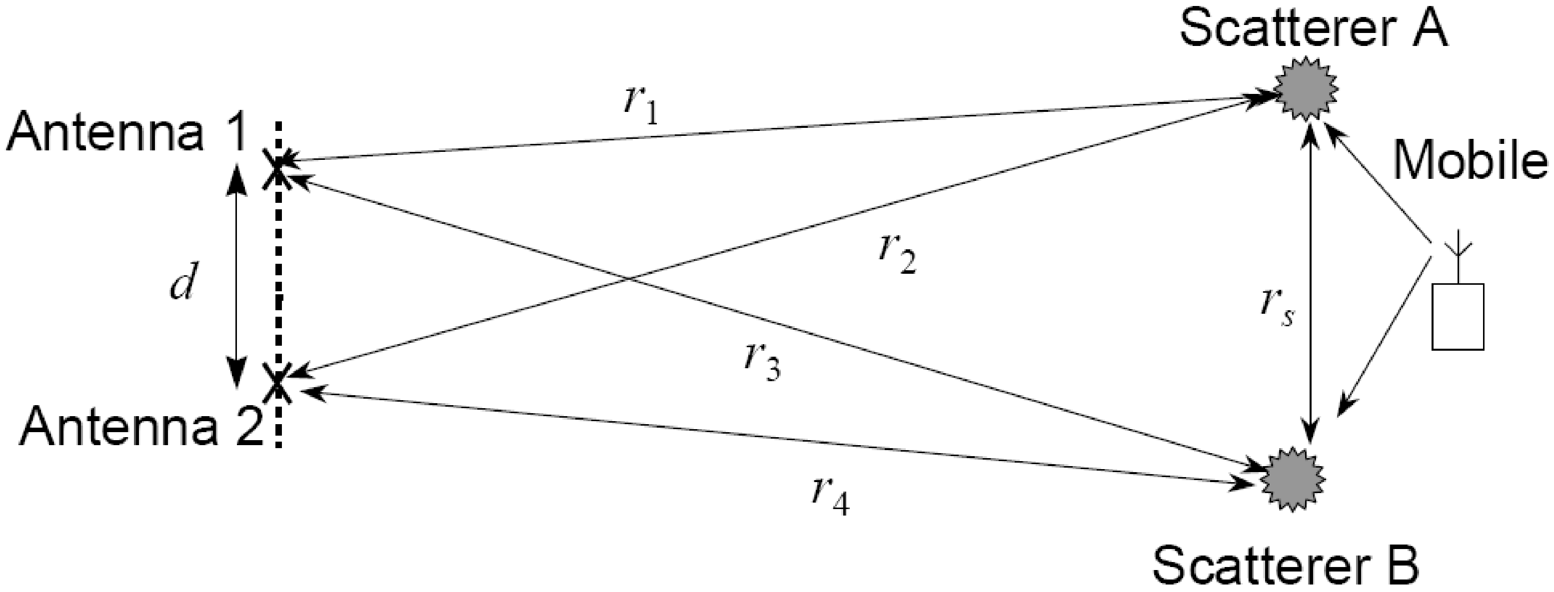
$$P_i = \frac{E\left[|\alpha_i|^2\right]}{2}$$

- Effective combiner

Type of diversity

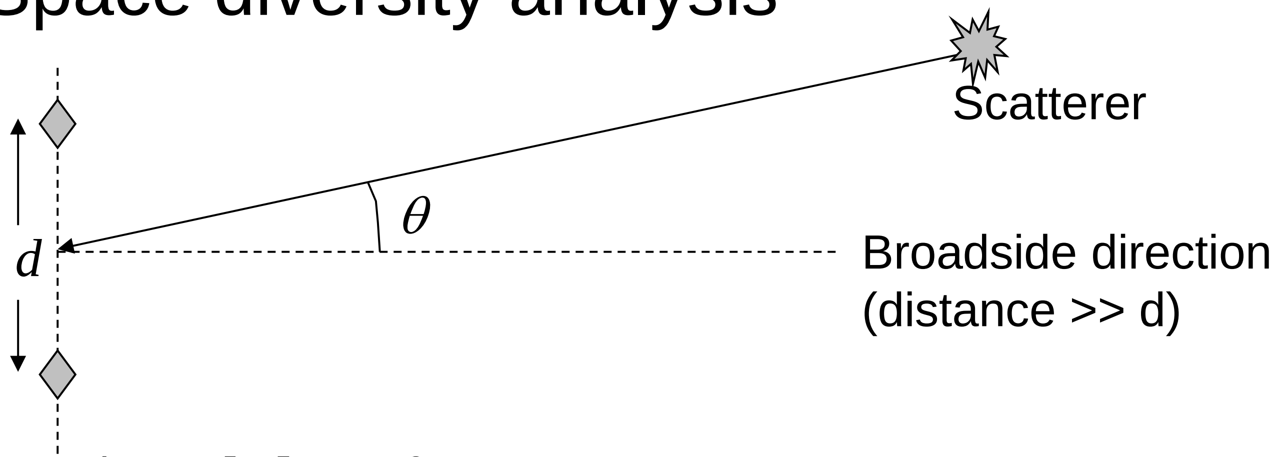
- Space diversity
  - Vertical
  - Horizontal
- Angle diversity
- Routing diversity
- Frequency diversity
- Time diversity
- Polarisation diversity

Space diversity



- Large antenna spacing or large scatterer spacing produces large path length differences
- Hence multipath will combine differently at each antenna

Space diversity analysis



Phase difference $$\phi = -kd\sin\theta$$

Signals from one scatterer $$\alpha_1 = r \qquad \alpha_2 = re^{j\phi}$$

Signals from n_s scatterers $$\alpha_1 = \sum_{i=1}^{n_s} r_i \qquad \alpha_2 = \sum_{i=1}^{n_s} r_i e^{j\phi_i}$$

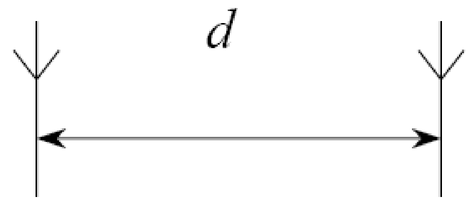
Correlation (Rayleigh) $$\rho_{12} = E\left[\sum_{i=1}^{n_s} e^{-j\phi_i}\right] = E\left[\sum_{i=1}^{n_s} e^{jkd\sin\theta_i}\right]$$

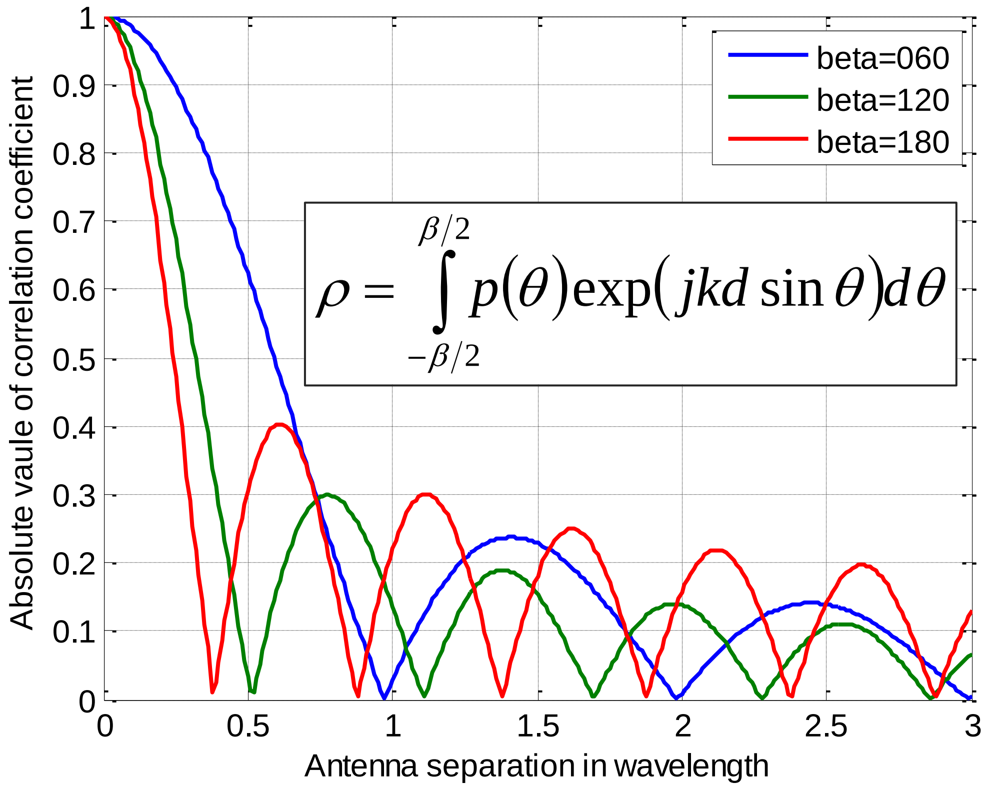
Evaluate expectations $$\rho_{12}(d) = \int_0^{2\pi} p(\theta) e^{jkd\sin\theta} d\theta$$

angle of arrival

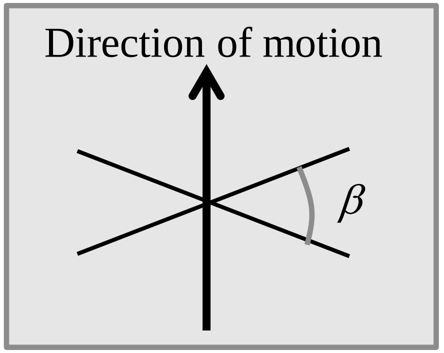
Horizontal space diversity

- Take $p(\theta) = 1 / 2\pi$
- Then $\rho(d) = J_0\left(\frac{2\pi d}{\lambda}\right)$

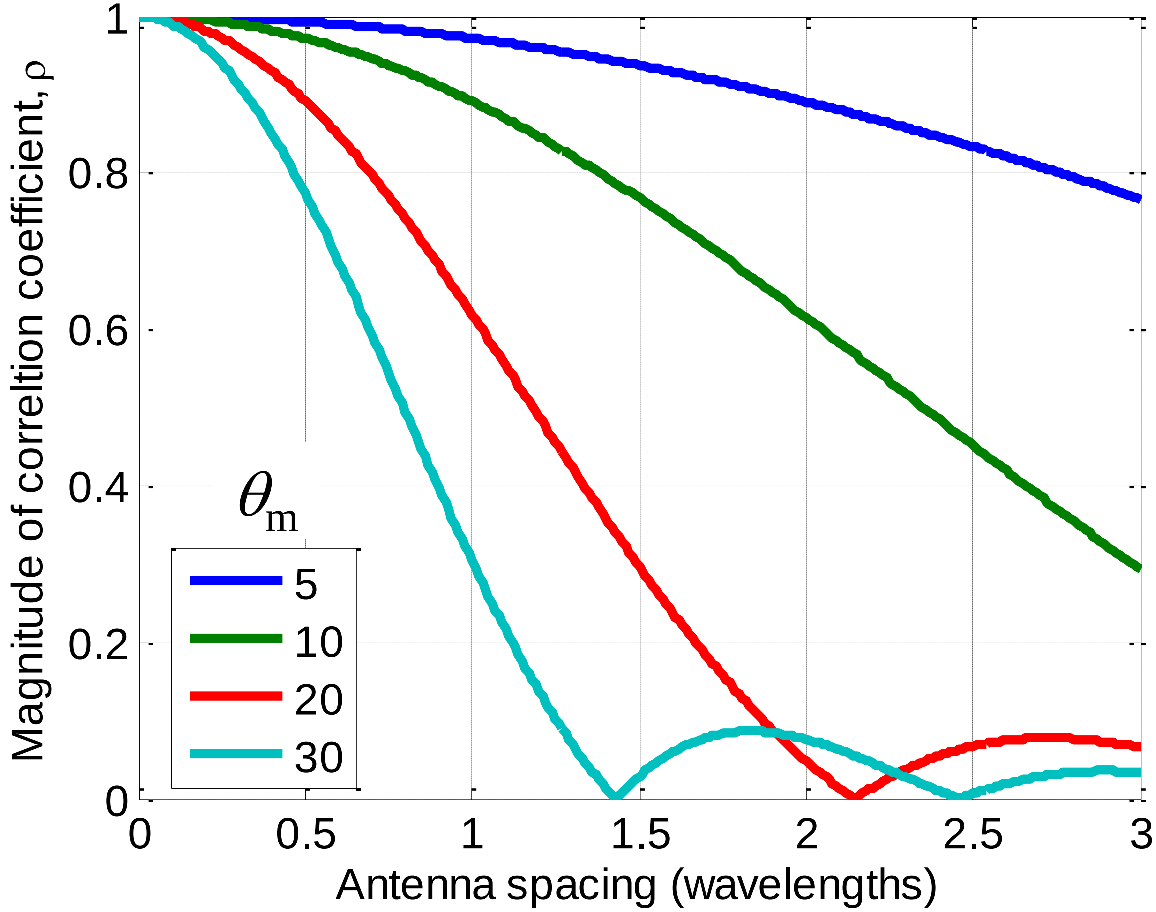




Required spacing may be reduced further when antenna coupling is considered



Vertical space diversity

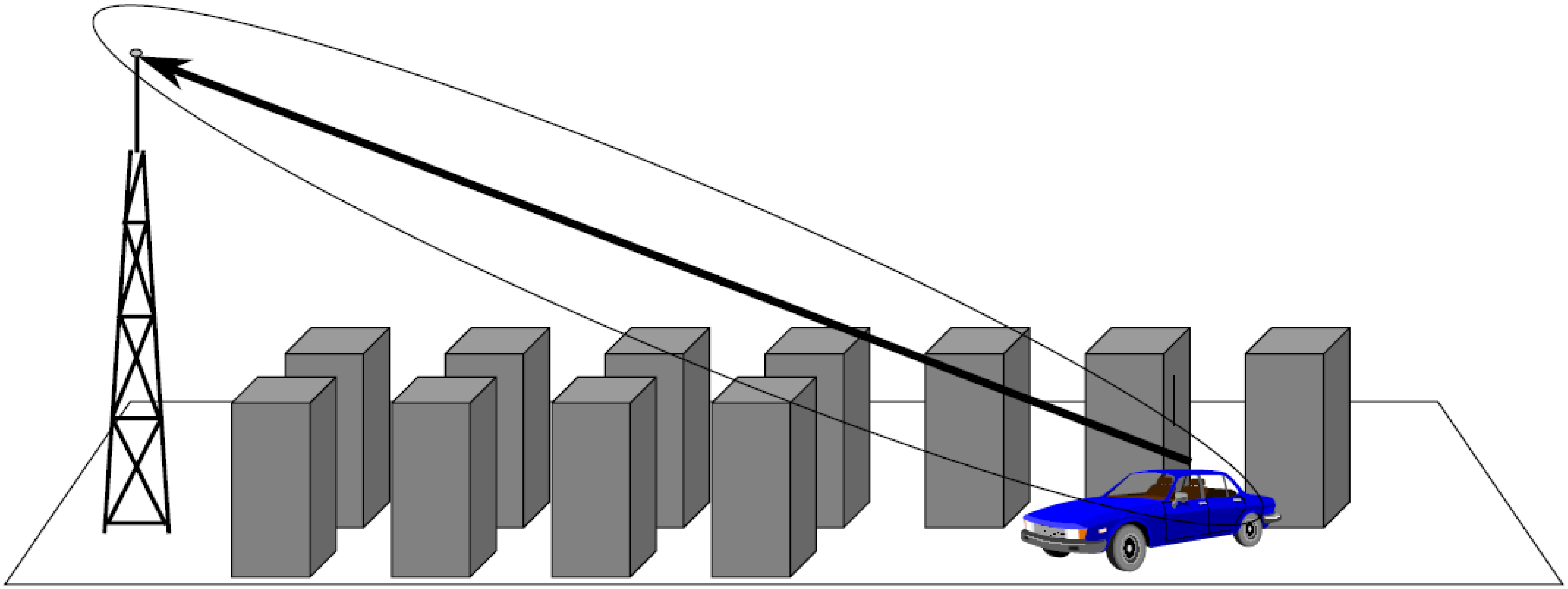


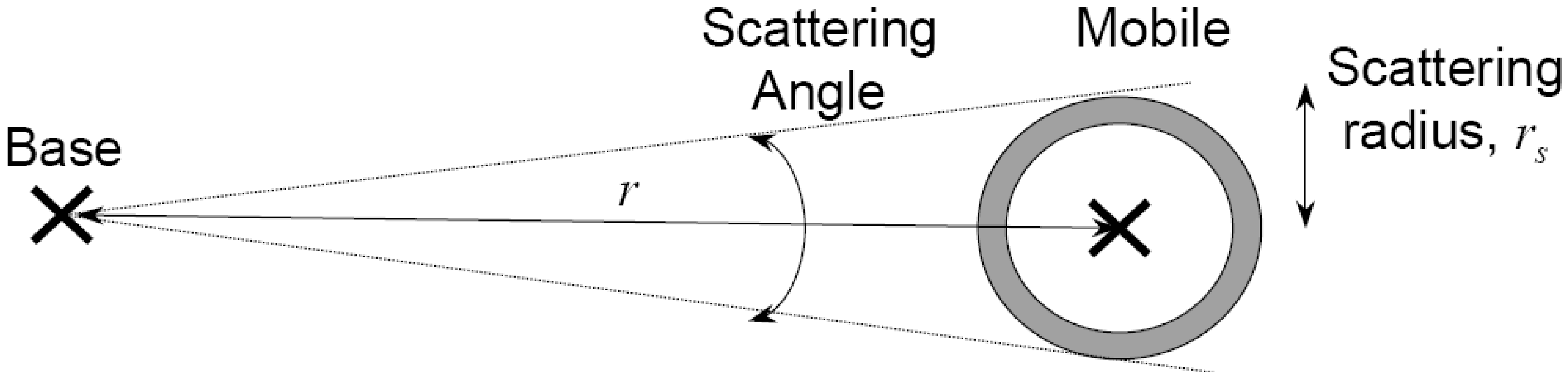
$$p(\theta) = \begin{cases} \frac{\pi}{4|\theta_m|}\cos\left(\frac{\pi\theta}{2\theta_m}\right) & |\theta| \le |\theta_m| \le \frac{\pi}{2} \\ 0 & \text{elsewhere} \end{cases}$$

$$\rho(d) = \int_{-\theta_m}^{\theta_m} p(\theta) e^{jkd\sin(\theta)} d\theta$$

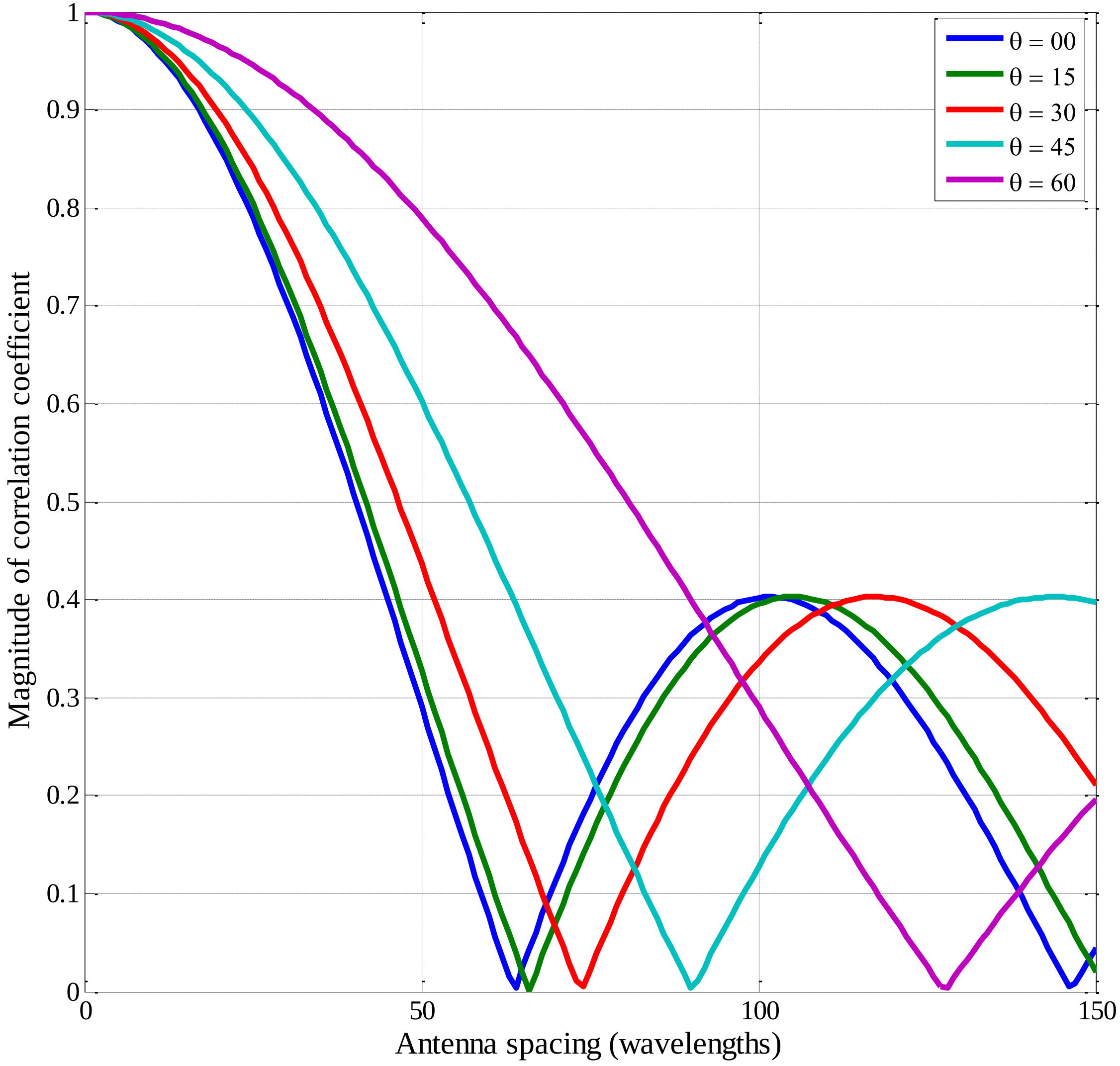
Restricted angle spread $(-\theta_m, \theta_m)$ such that greater separation is needed

Base station space diversity





Horizontal spaced macrocell base station antennas

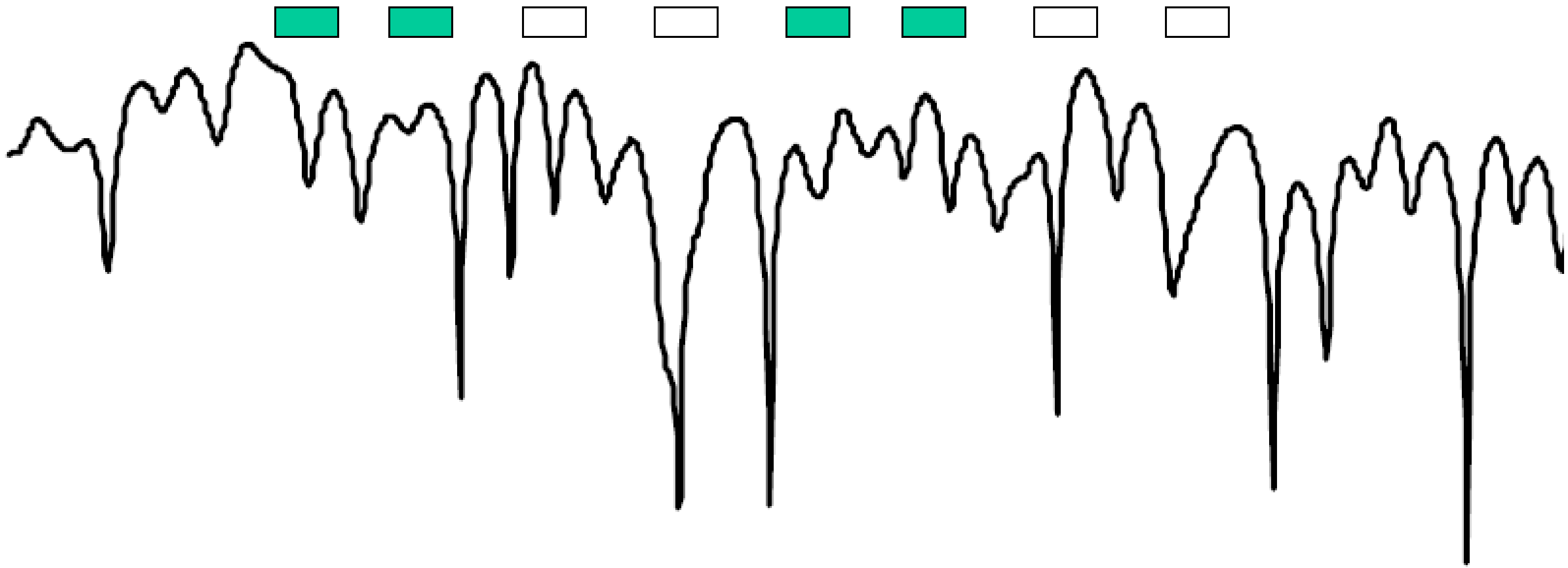


Scattering radius 0.6% of base-mobile range

Polarisation diversity

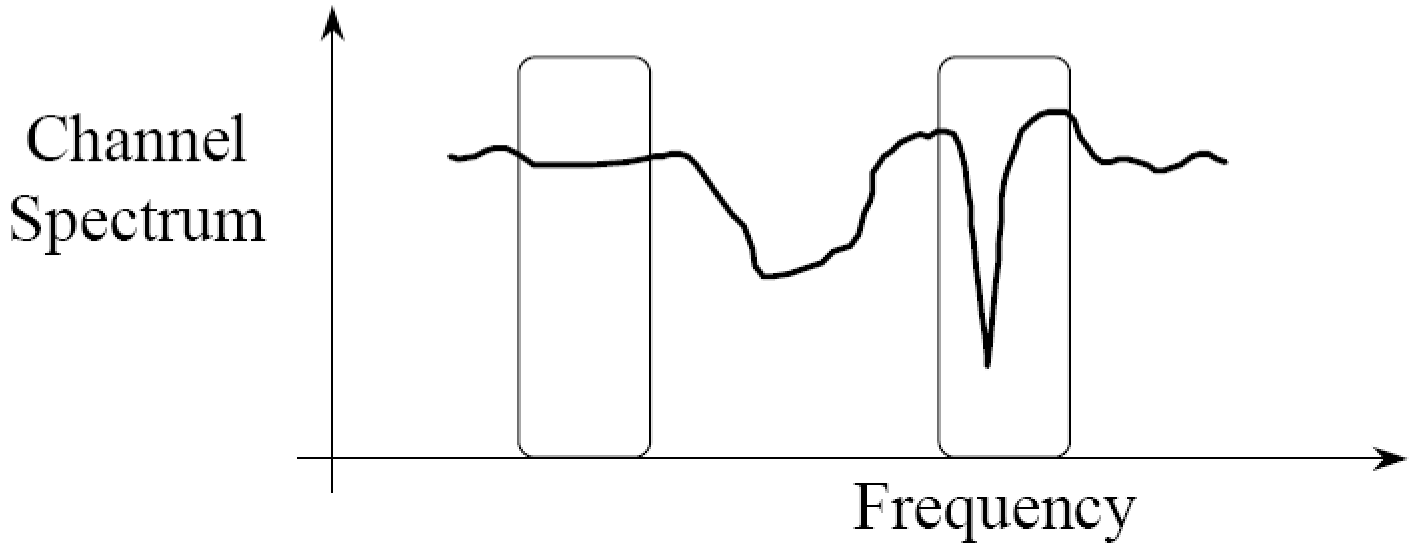
- Reflected and diffracted signals depolarises
- Base station polarisation diversity may help when users held handsets at about 45° to the vertical
- At the base station horizontal and vertical components are almost uncorrelated, but the cross-polar component is weak
- Polarisation diversity more attractive at mobile station, as it works with limited space, but it is more complex

Time diversity



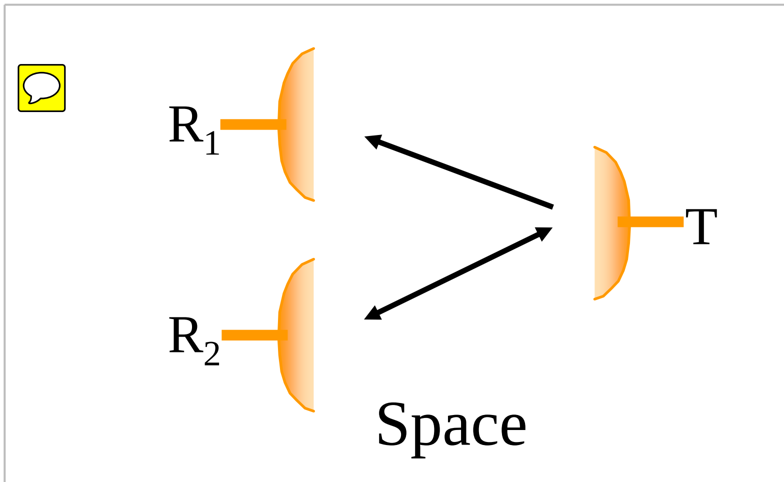
- Retransmit with Time Separation
- Advantage: Need only one receiver
- Disadvantage: Wastes bandwidth, adds delay

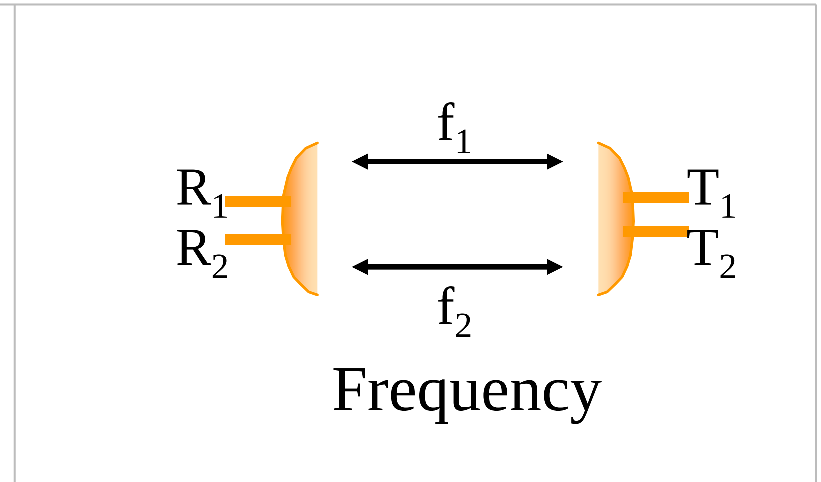
Frequency diversity

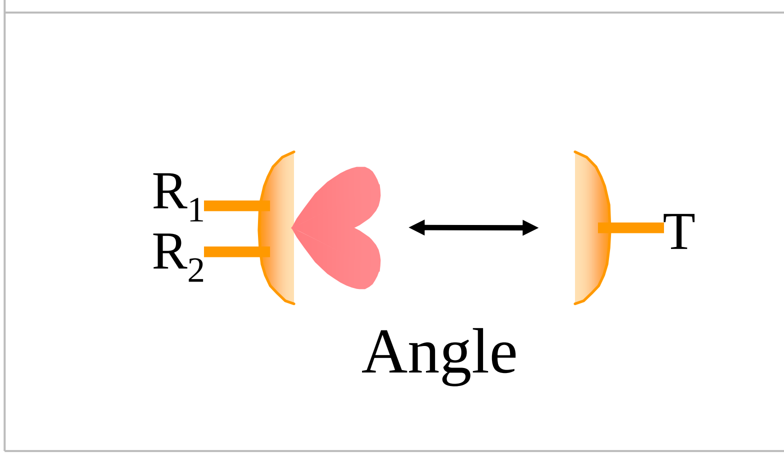


- Wideband Channel
- Simultaneous Transmission
- Wastes power and bandwidth
- Equalisers...

High capacity LOS links showing diversity reception





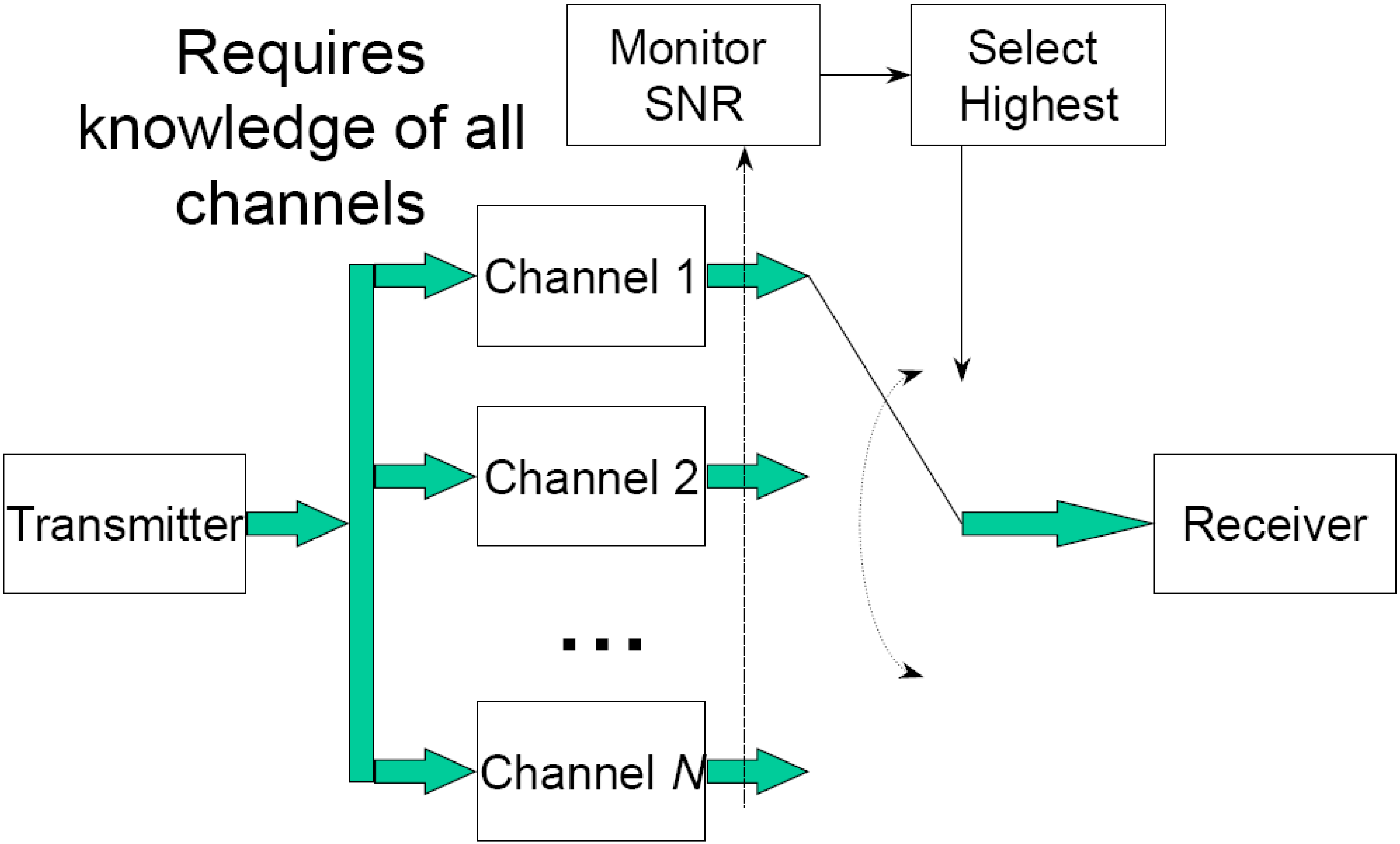


Also combinations of space, frequency, and route

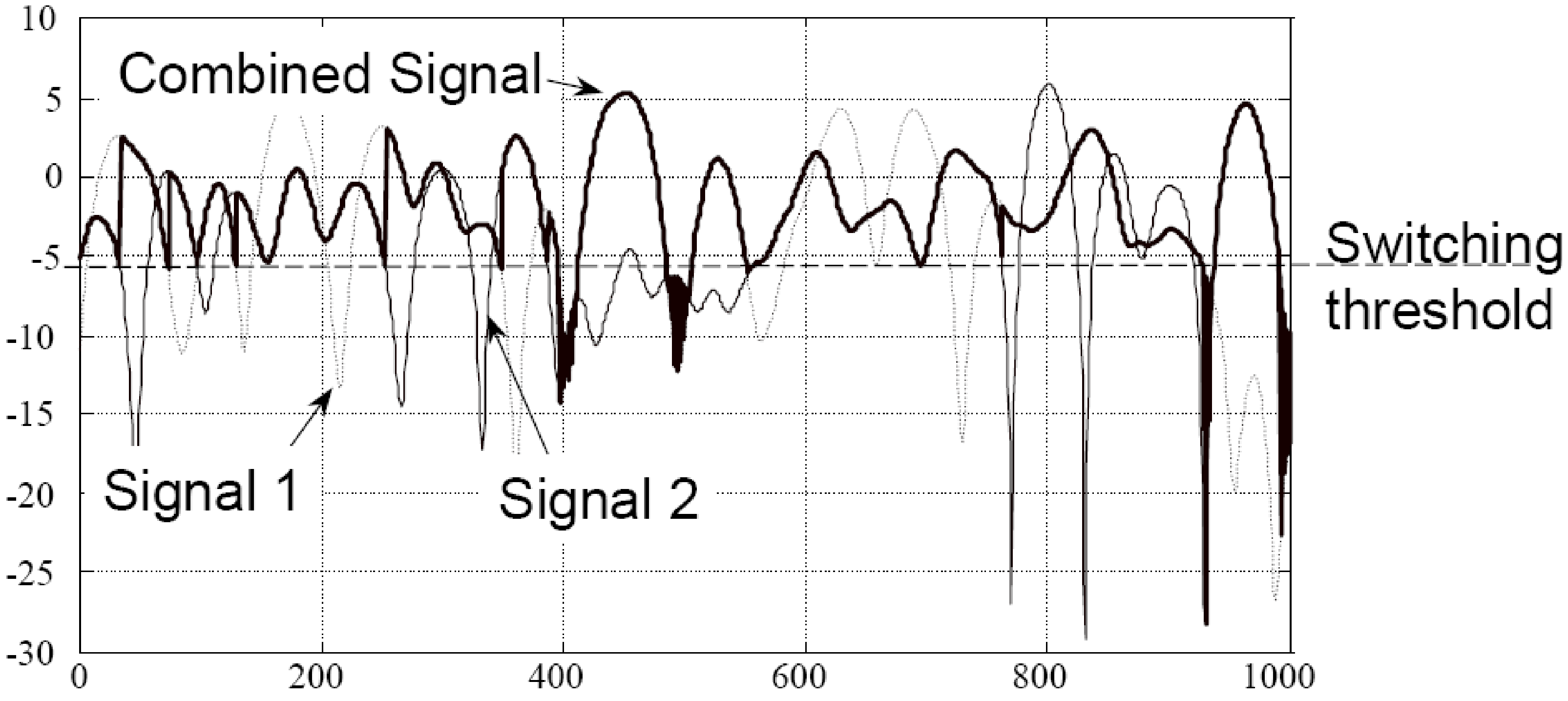
Combining techniques

- Selection Combining
- Switched Combining
- Equal Gain Combining
- Maximal Ratio Combining

Selection combining

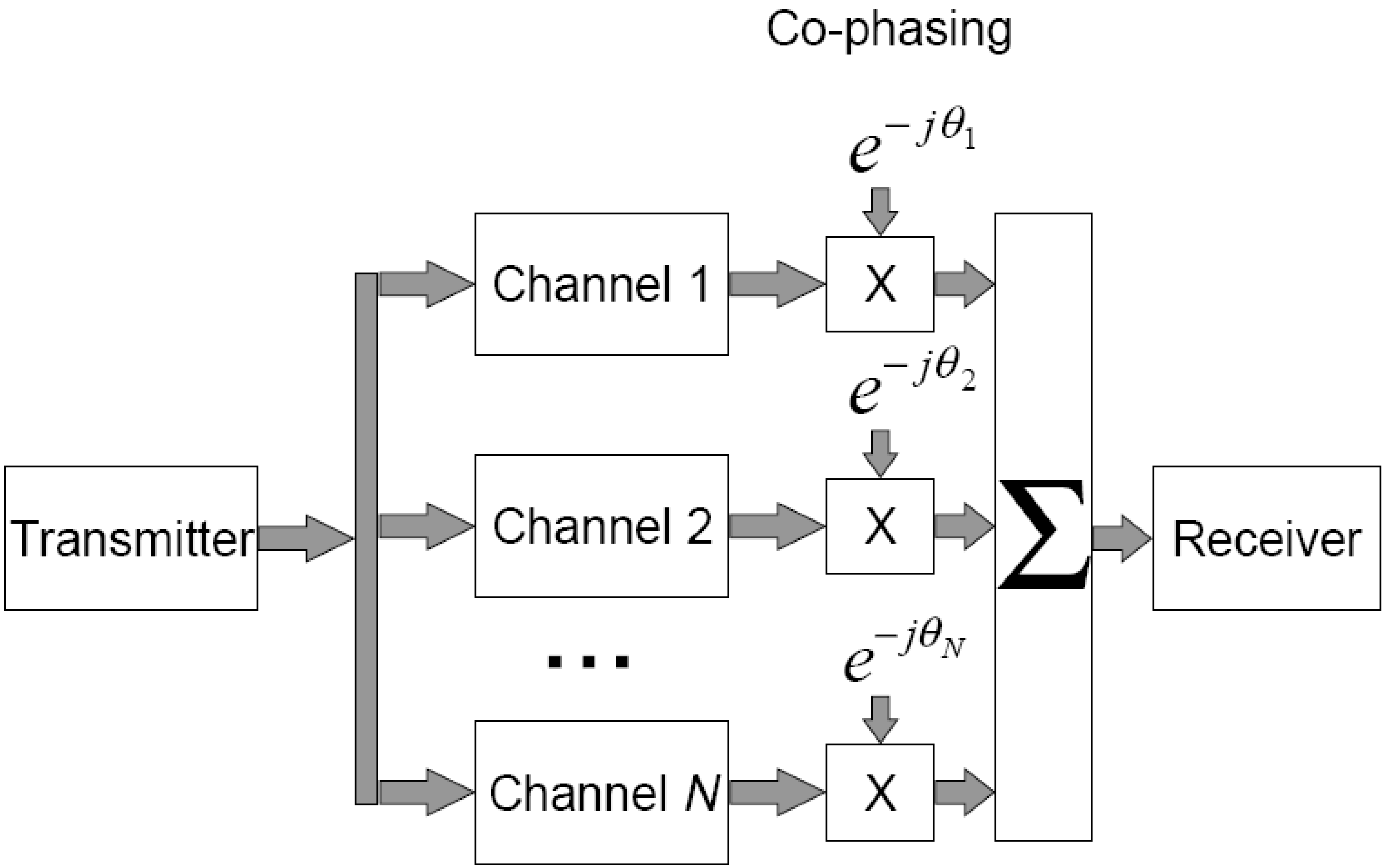


Switched combining

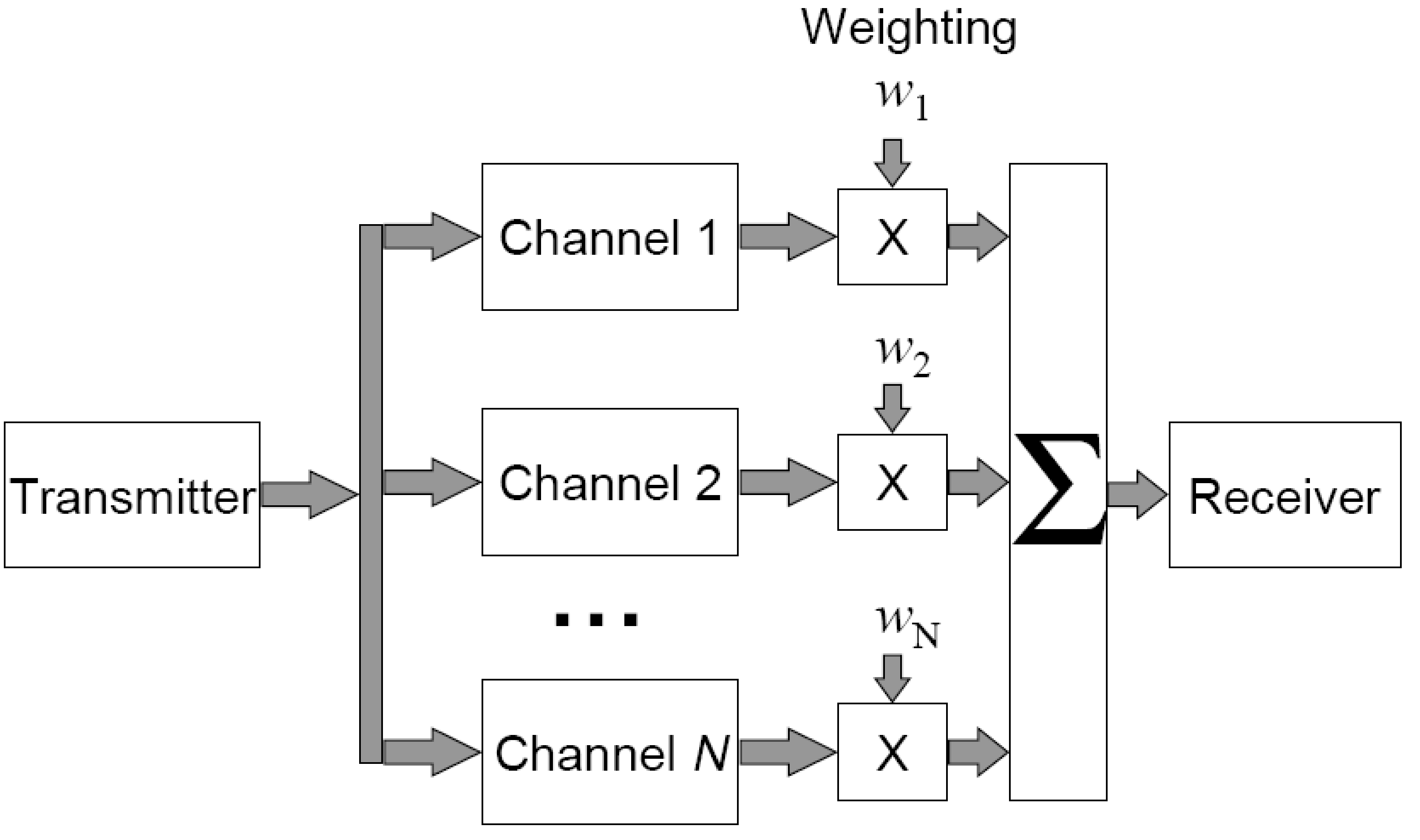


- Avoids multiple receivers
- ‘Switch and stay’ strategy
- Must set appropriate threshold relative to mean level
- Performance always worse than selection combining

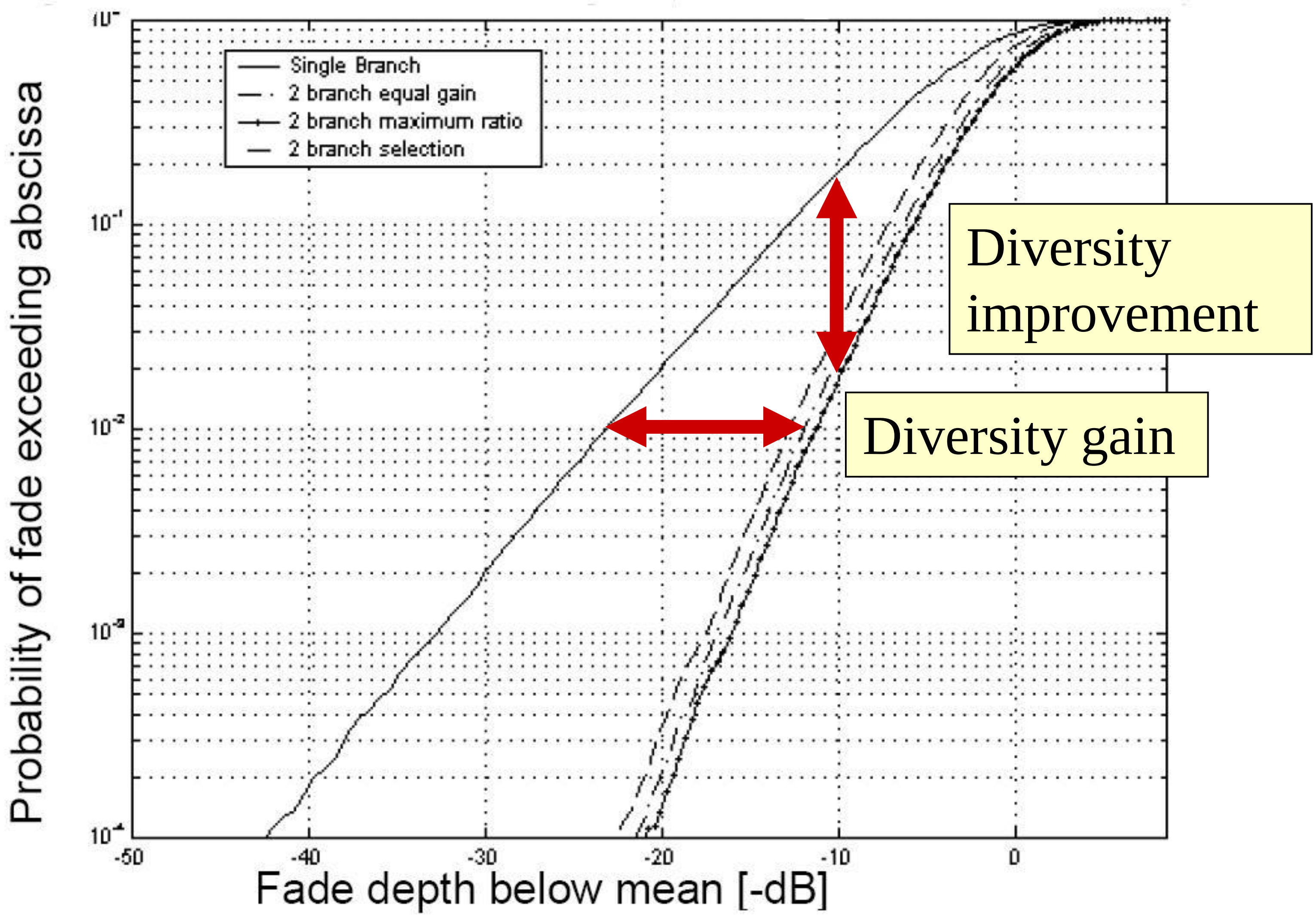
Equal gain combining



Maximum ratio combining



Comparison of combining techniques



Conclusions

- Diversity effectively overcomes multipath fading
- Large gains (e.g. 10 dB) relatively easy to provide
- Costs in extra hardware (antennas, receivers, combiner)
- Requires low correlations and significant mean powers