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(54) **Method for optimizing the spacing between receiving antennas of an array usable for counteracting both interference and fading in cellular systems**

(57) The spacing between adjacent receiving antennas of an ULA located in a base station of a cellular communication system is optimized to both the channel and the interference space-time multipath. The spacing is larger than the canonical $\lambda/2$ for introducing a certain degree of angular equivocation aimed to see the interferers (all or a certain number depending on the degree of freedom of the directivity function) as they were grouped together along an unique direction. In an ideal case of fixed interferers with null angular power spread, a given cellular planning and known aperture of the array, the optimal spacing Δ_{opt} between adjacent antennas is directly calculable in closed mathematical form in function of the equal angular separation $\Delta\theta$ between the DOAs of the interferers. When the restrictive hypotheses are neglected, the optimal spacing Δ_{opt} is calculable as the spacing that minimizes the spread between the N_i wave numbers associated to the barycentric DOAs of the N_i interfering

cells. Moreover closed form solution can be dealt with on condition that N_i interfering cells (with one broadside interfering cell) are considered; said angular separation between the interferers is assumed as being the average $\Delta\theta^B$ among adjacent angular separations between barycentric DOAs weighted by the respective barycentric received power. Assuming a multipath channel with an arbitrary number of paths N_p , the i^{th} barycentric DOA is calculated by executing a weighted average extended to the $N_p \times S$ directions of arrival of the N_p paths by the S points of a grid indicative of the positions spanned by the i^{th} interfering station inside its cell, weighting each DOA by the power received on that path. In a SIMO scenario with square cell planning according to the fixed or mobile WiMAX IEEE 802.16d802.16-2004/e, the value $\Delta_{opt}=1.8\lambda$ is found as an optimum trade-off between beamforming and diversity (fig.5).

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Description**FIELD OF THE INVENTION**

[0001] The present invention relates to the field of wireless telecommunications networks, and more precisely to a method for optimizing the spacing between receiving antennas of an array usable for counteracting both interference and fading in cellular systems. The invention is suitable to be employed in the Base Station receivers of multi-cell wireless systems based on frequency reuse in adjacent cells and, if needed, employing the SDMA technique in the same cell. The invention could find particular application in cellular systems based on different types of radio access, either narrowband or broadband, such as GSM, UMTS, WiMAX IEEE 802.16-2004, WiMAX IEEE 802.16e, HiperMAN ETSI. TS 102 177, etc. The invention could also be applied, with obvious modifications anyway covered by the claims, to receivers belonging to Subscriber Stations and/or point-to-point links.

BACKGROUND ART

[0002] As known, the multipath fading together with co-channel interference from subscriber stations in the same or adjacent cells, are the major sources of SINR degradation at the output of the receivers. When using a Base Station (BS) with multiple antennas, the multi-cell interference is accounted by a spatial covariance matrix (or noise power) that is assumed as constant, and applying a spatial filter on the received signals (and a pre-filter at the transmitter whenever available) to improve the SINR at the output.

[0003] Multiple antennas (SIMO/MIMO) are a known manner to obtain larger values of SINR. When designing the antenna array, diversity and beamforming are two different strategies typically adopted depending on the specific impairment, either fading or interference, that has to be contrasted. There are some freedoms in the design of the arrays so as in the design of the reception signal processing.

- Diversity-oriented schemes take advantage of the spatial redundancy over uncorrelated fading for reducing the fading margin. Large antenna spacing compared to the carrier wavelength λ is used, say larger than $5-8 \lambda$, so that signals are uncorrelated at the different antennas and can be processed by diversity-oriented algorithms, such as Selection Combining or MRC. These algorithms need the knowledge of channel responses at all antennas.
- Beamforming-oriented schemes for interference rejection are based on small spacing up to $\lambda/2$ so that signals are completely correlated at different antennas and
- Beamforming-oriented schemes for interference rejection are based on small spacing up to $\lambda/2$ so that signals are completely correlated at different antennas and beamforming techniques (e.g. MVDR) are adopted to filter out the interferences. Used algorithms require the knowledge of both channel response and the spatial features of the interference power.

[0004] Usually the spacing between adjacent antennas is not optimized to the channel/interference parameters and to the receiver scheme. Small spacing is typically adopted in LOS environments where beamforming is more effective in filtering the interference. On the other hand, NLOS applications call for diversity-oriented approaches. Still, most of the environments are characterized by mixed LOS/NLOS conditions and they need an optimized spacing whose value is between the two extreme cases mentioned above.

[0005] In the paper of S. Savazzi, O. Simeone, U. Spagnolini, titled: "Optimal design of linear arrays in a TDMA cellular system with Gaussian interference", IEEE Proc. SPAWC 2005 [SPAWC], an optimal design of a non-uniform symmetric array is carried out by maximizing the channel capacity. Numerical simulations showed that substantial capacity improvements can be achieved by an exhaustive search over the optimization domain. The capacity maximization proposed in [SPAWC] is shown to be difficult in practice even when considering the uniform linear array case, under specific assumptions on the structure of the cellular planning.

[0006] As known, a spacing larger than $\lambda/2$ introduces a certain degree of angular equivocation in the directivity function of the ULA, aimed to induce the latter to see the interferers (all or a certain number depending on the degree of freedom of the directivity function) as grouped together along an unique apparent direction. In other words, the minimization of the spread of the wave numbers (spatial pulsations of the array directivity function) results in the maximization of the array interference suppression capability. This should allow to release some degrees of freedom of the directivity function, so that a corresponding number of zeroes could be placed at the angular positions they mostly were needed, for example in correspondence of the common direction of the interferers for a deeper attenuation. The optimal theoretical spacing Δ_{opt} is calculable in known way under the following restrictive hypotheses: a) null angular spread on the channel; b) interfering terminals are located in fixed positions with main DOAs symmetric with respect to the broadside

direction; c) all terminals transmit with maximum power.

[0007] The theoretical approach of above is only valid for an unreal scenario of null angular spread which does not exist at all in the real radio communications, especially cellular. With that, the equivocation expression for Δ_{opt} only accounts for simple geometrical relations.

OBJECT AND SUMMARY OF THE INVENTION

[0008] Object of the invention is that of obtaining the optimum spacing in closed mathematical form when real radio paths are taken into account without needing of demanding simulations, limitedly to an uniform linear array under some specific assumptions on the structure of the cellular planning and the interference .

[0009] In view of above, the invention provides a method for optimizing the spacing between the antennas of a receiving uniform array usable in a receiving station, either fixed or mobile, of a cellular communication system, as disclosed in claim 1.

[0010] According to the method of the invention, a closed form expression for the optimal spacing, which is function of the positions of the interfering cells and the angular power density of the multipath is proposed as solution of the spatial spread minimization problem.

[0011] According to the method of the invention, there is not the need of explicitly recurring to any minimization algorithm, but instead the theoretical expression known for the unreal scenario is adapted to the real case. The spacing so calculated is automatically optimized to the channel/interference parameters, and could be larger than the canonical $\lambda/2$ for trading between large spacing to take advantage of diversity and small spacing to have accurate interference rejection capability. This is suitable for either LOS, NLOS or mixed LOS/NLOS propagation environments.

[0012] According to the method of the invention, some significant restrictive hypotheses mentioned above are neglected, and the new ones are considered: A) the channel gathering the complex gains at the N_R receiving antennas is modelled as a space-time multipath power profile characterized by angular-delay dispersion; B) terminals are randomly distributed within the respective cells; C) fast-fading and shadowing power fluctuations are considered; D) path-loss attenuation is considered conforming, for example, the Hata-Okumura model; E) all terminals regulate the transmission power according to an adaptive modulation, based on the channel state, so as to satisfy a fixed bit error rate ($\text{BER} = 10^{-6}$);

[0013] The only pre-condition for the method is the symmetry of the main interfering paths with respect to the broadside direction of the array, to say, we are considering a planning by which the normal to the line crossing all antennas of the array is crossed by an interfering cell and the other interfering cells are symmetrically disposed with respect to the broadside direction. This is a reasonably assumption valid for all the most popular planning, e.g. square, hexagonal, etc. To match with the symmetry condition, rigorously, the interferer should be placed at the centre of the cell, in such a case the motion of the transmitter should not be accounted. The method of the invention overcomes this limitation by considering the motion of the interfering user as it happen in correspondence of the points of a grid used to spread the multipath over the complete cell.

[0014] The adaptation of the theoretical expression of the equivocation to the real multipath is carried out by introducing the concept of barycentric DOAs of the N_I interfering cells. Accordingly, the multipath generated by the i^{th} interferer

station ideally collapses in a single path characterized by a barycentric DOA θ_i^B and a barycentric received power

P_i^B . Referring to the i^{th} interfering cell, with $i=1, \dots, N_I$, the i^{th} barycentric DOA, is calculated from the power-angle profile of the channel between the interfering station located in the i^{th} cell and the receiving station located in the cell of interest, when the spatial location of the interfering station is randomly distributed within its cell. Assuming a multipath channel with an arbitrary number of paths N_p , the i^{th} barycentric DOA is calculated by executing a weighted average extended to the $N_p \times S$ directions of arrival of the N_p paths by the S points of a grid indicative of the positions spanned by the i^{th} interfering station inside its cell, weighting each DOA by the power received on that path.

[0015] Once the barycentres have been calculated, the successive step is that to find an angular separation between the interferers to be introduced into the theoretical expression to get the maximum equivocation, and hence the optimal spacing Δ_{opt} . According to the method of the invention, this is done calculating a weighted average barycentric DOA separation $\Delta\theta^B$ and introducing it into the theoretical expression of the maximum equivocation. Operating as said above on the barycentres, the calculated optimal spacing Δ_{opt} is the spacing that minimizes the spread between the N_I wave numbers associated to the barycentric DOAs of the N_I interfering cells. The advantage is that a brute-force minimization is avoided.

[0016] In a scenario with square cell planning and receiving array with 90° aperture, the value $\Delta_{\text{opt}}=1.8\lambda$ is obtained as an optimum trade-off between beamforming and diversity. Other types of cellular planning have been investigated too.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] The features of the present invention which are considered to be novel are set forth with particularity in the appended claims. The invention and its advantages may be understood with reference to the following detailed description of an embodiment thereof taken in conjunction with the accompanying drawings given for purely non-limiting explanatory purposes and wherein:

- **fig.1** shows the frame structure for the uplink SIMO channel compliant with IEEE 802.16-2004 specification for (fixed) WiMAX;
- **fig.2** shows an exemplary frame structure for uplink SIMO channel compliant with IEEE OFDMA-TDMA specification for (mobile) WiMAX 802.16e;
- **fig.3** shows a typical uplink interferer scenario in a wireless cellular system for the reception by a Base Station BS_0 of the signal transmitted by the user SS_0 ;
- **fig.4** shows a diagram useful to evaluate the interference power;
- **fig.5** shows the interfering scenario of fig.3 with assumed initial positions of the fixed interferers;
- **fig.6** shows an optimally spaced ULA for a given system planning;

DETAILED DESCRIPTION OF AN EMBODIMENT OF THE INVENTION

[0018] In order to simplify the radio channel description and the whole calculations and in meanwhile achieving a satisfactorily generalization, the embodiment is referred to a SIMO configuration for WiMAX-compliant systems, either fixed or mobile, but the same concepts and results are applicable to GSM, UMTS, etc., without changing the guidelines of the method.

[0019] As known, in each cell of a WiMAX-compliant system the multiple access is handled by a combination of time, frequency, and/or space division. With reference for example to **fig.1** for fixed/nomadic WiMAX and **fig.2** for mobile WiMAX, within the available bandwidth, composed of N subcarriers, the transmission is organized in L time-frequency resource units, called blocks (or bursts), each containing $K < N$ subcarriers and a time window of L_s OFDM symbols. Each block includes both coded data and pilot symbols. Pilot subcarriers are distributed over the block to allow the estimation of the channel/interference parameters. In addition to these distributed pilot subcarriers, a preamble containing only known training symbols could also be included in the block, as shown in the example of **fig.1**. In this case, the preamble is used for the estimation of the channel/interference parameters, while the other pilot subcarriers are used to update the parameters' estimate along the block. Note that the same time-frequency unit may be allocated to more users in case SDMA is adopted. Every OFDM symbols of each block includes a subset of pilot subcarriers used to track the channel estimation in fast time-varying channels.

[0020] With reference to **fig.3**, let us consider a subscriber station among those simultaneously active in the cell, say SS_0 , transmitting (or receiving) signals to (or from) its own base station BS_0 (the communication can be either in the uplink or in the downlink). The transmitter is assumed to employ a single antenna, while the receiver has N_R antennas. The scenario of interest is exemplified for a squared cellular layout with frequency reuse factor $F=4$. This example refers to an uplink communication, where the transmission by SS_0 to BS_0 is impaired by the interference from $N_I = 3$ out-of-cell terminal stations $\{SS_i\}_{i=1}^{N_I}$ that employ the same subcarriers as SS_0 . In the figure, d_i denotes the distance of the i^{th} terminal from its base station for $i=0, \dots, N_I$, while d_{i0} is the distance of the interferer SS_i (with $i \neq 0$) from the base station BS_0 of the user of interest.

SIMO SYSTEM AND SIGNAL MODEL

[0021] Focusing on uplink communications, the transmitter at the station SS_0 maps the sequence of data to be transmitted to BS_0 into a sequence of blocks, indexed by $\ell=1,2,\dots,L$. (figures 1 and 2). In the following the symbol ℓ is disregarded because the given expressions are valid for every ℓ . The signals received by the N_R receiving antennas on the k^{th} subcarrier can be written as:

$$\mathbf{y}_k = \mathbf{h}_k \cdot x_k + \mathbf{n}_k, \quad (1)$$

where:

$$\mathbf{h}_k = [h_{1,k} \cdots h_{N_R,k}]^T \quad (2)$$

is the spatial vector containing the N_R complex channel gains for the N_R receiving antennas, while x_k denotes the symbol (either pilot or data) transmitted on the k^{th} subcarriers.

[0022] Data symbols can be generated according to an adaptive modulation-coding scheme where the transmission mode is selected based on the channel state (see, as an example, the transmission modes for IEEE-802.16-2004 in **TABLE 1 (APPENDIX A)**). The $N_R \times 1$ vector $\mathbf{n}_k$, modelling both the background noise and the out-of-cell interference, is assumed to be zero-mean complex (circularly symmetric) Gaussian, temporally uncorrelated but spatially correlated with spatial covariance $\mathbf{Q}$, where:

$$E[\mathbf{n}_k \cdot \mathbf{n}_{k+n}^H] = \mathbf{Q} \delta(n). \quad (3)$$

Here $\delta(\cdot)$ denotes the Dirac delta, while the index n spans the subcarriers. The channel vector $\mathbf{h}_k$ is assumed to be constant within the block. It varies from block to block in case of mobile applications (fast-varying channels), while it can be considered as constant over several blocks for fixed/nomadic systems (slow-varying channels). Active interferers may be indeed different in each block, as the access is uncoordinated (not synchronized) between cells. In **fig.3**, for instance, the interferer SS_1 may stop at any given time and a new terminal may become active in the cell, generating an abrupt change in the signal interfering on user SS_0 . Furthermore, in case of frame structures as the one exemplified in **fig.1**, the interference covariance could also vary within the block, on each OFDM symbol. By gathering signals (1) for the K useful subcarriers into the $N_R \times K$ matrix $\mathbf{Y} = [\mathbf{y}_1 \cdots \mathbf{y}_K]$, the signal model can be rewritten in the standard matrix notation:

$$\mathbf{Y} = \mathbf{H}\mathbf{X} + \mathbf{N} \quad (4)$$

where $\mathbf{H} = [\mathbf{h}_1 \cdots \mathbf{h}_K]$ is the $N_R \times K$ space-frequency channel matrix, whose element (m,k) represents the channel gain for the m^{th} receiving antenna on the k^{th} subcarrier. The $K \times K$ diagonal matrix $\mathbf{X} = \text{diag}\{x_1, \dots, x_K\}$ contains the transmitted symbols.

The model above is general and it applies to several cases such as:

- Frame structures where the block is composed by a preamble and a data field containing pilots (see example in **fig.1**), such as in the physical layer of WiMAX IEEE 802.16-2004 systems. Being these systems suitable for fixed applications, the preamble can be used to estimate the channel/interferer parameters, while the pilots are exploited to track the non-stationary interference parameters.
- Frame structures where the block does not contain the preamble and pilot subcarriers are inserted in data-bearing OFDM symbols (see example in **fig.2**), such as in the physical layer of WiMAX IEEE 802.16e systems. These systems are suitable for mobile applications, thus the pilots can be used to track both the channel and interference parameters.
- Decision feedback receivers where estimated data symbols are used as pilot symbols for the estimation of channel/interference parameters.

SIMO CHANNEL MODEL

[0023] In order to model the space-frequency matrix $\mathbf{H}$, it is useful to write it in terms of the $N_R \times W$ space-time channel matrix $\tilde{\mathbf{H}}$ that gathers by columns the W taps of the discrete-time channel impulse response in the time-domain:

$$\mathbf{H} = \tilde{\mathbf{H}}\mathbf{F}^T. \quad (5)$$

The element (k, w) of the $N_R \times W$ matrix $\mathbf{F}$, for $k=1, \dots, K$ and $w=1, \dots, W$, is defined as:

$$F_{k,w} = \exp \left[-\frac{j2\pi}{N} n_k (w-1) \right], \quad (6)$$

with $n_k \in \{0, \dots, N-1\}$ denoting the frequency index for the k^{th} useful subcarrier and N the total number of subcarriers. The multiplication by $\mathbf{F}$ in (3) performs the DFT transformation of the matrix $\tilde{\mathbf{H}}$ by rows.

The propagation channel between SS₀ and BS₀ (fig.3), the space-time matrix $\mathbf{H}$ is assumed to be the superposition of N_p paths' contributions. Each path, say the r^{th} , is described by a direction of arrival (DOA) at the receiving array $(\theta_{0,r})$, a delay $(\tau_{0,r})$ and a complex fading amplitude $(\alpha_{0,r})$:

$$\tilde{\mathbf{H}} = 10^{\frac{P_0^{(R)}}{20}} \sum_{r=1}^{N_p} \alpha_{0,r} \mathbf{a}(\theta_{0,r}) \mathbf{g}^T(\tau_{0,r}) = \mathbf{S} \mathbf{A} \mathbf{G}^T. \quad (7)$$

The $N_p \times 1$ vector $\mathbf{a}(\theta_{0,r})$ denotes the array response to the direction of arrival $\theta_{0,r}$ ($\theta_{0,r}=0$ denotes the broadside), while the $W \times 1$ vector $\mathbf{g}(\tau_{0,r})$ collects the symbol-spaced samples of the waveform $g(t-\tau_{0,r})$, that is the cascade of transmitter

and receiver filters shifted by the delay $\tau_{0,r}$. The fading amplitudes $\{\alpha_{0,r}\}_{r=1}^{N_p}$ are assumed to be uncorrelated and to

have normalized power-delay-angle-profile $\Lambda_{0,r} = \mathbf{E}[|\alpha_{0,r}|^2]$ so that $\sum_{r=1}^{N_p} \Lambda_{0,r} = 1$. The matrices $\mathbf{S} = [\mathbf{a}(\theta_{0,1}) \dots \mathbf{a}(\theta_{0,N_p})]$,

$\mathbf{G} = [\mathbf{g}(\tau_{0,1}) \dots \mathbf{g}(\tau_{0,N_p})]$, and $\mathbf{A} = \text{diag}(\alpha_{0,1}, \dots, \alpha_{0,N_p})$ in (7) gather the channel parameters for the whole multipath set.

Possible values of the parameters indicated by expression (7) are given by known multipath models, for example the temporal ones called SUI enriched with a characterization of the spatial interference (SUI-ST); see also **Table 2 (APPENDIX A)**.

[0024] The received power $P_0^{(R)}$ [dBm] in (7) is given by:

$$P_0^{(R)} = P_0^{(T)} + G - L(d_0) + S_0, \quad (8)$$

and it depends on: the transmitted power $P_0^{(T)}$ [dBm]; the transmitter-receiver antenna gain $G = G^{(T)} + G^{(R)}$ [dB]; the

power loss $L(d_0)$ [dB] experienced over the distance d_0 between SS₀ and BS₀; the random fluctuations $S_0 \sim N(0, \sigma_s^2)$ due to shadowing. As recommended in IEEE 802.16-2004, the path-loss is herein modelled according to the Hata-Okamura model:

$$L(d) = 20 \log_{10} \left(\frac{4\pi d_{\text{ref}}}{\lambda} \right) + 10\gamma \log_{10} \left(\frac{d}{d_{\text{ref}}} \right) + 6 \log_{10} \left(\frac{f_c}{2} \right) \quad (9)$$

with λ denoting the wavelength, γ the path-loss exponent, d_{ref} a reference distance, and f_c the carrier frequency [GHz].

Note also that $P_0^{(T)}$ is limited by the maximum power available at the SSs, i.e. $P_0^{(T)} \leq P_{\text{max}}^{(T)}$. The power random fluctuations described above have to be ascribed to variations of the user position inside the cell.

SIMO INTERFERENCE MODEL

[0025] The inter-cell interference is the limiting factor in the performance on estimating the channel, and hence of the system. It is assumed to be spatially correlated with covariance:

$$\mathbf{Q} = \mathbf{Q}_n + \mathbf{Q}_I \quad (10)$$

sum of the background noise matrix $\mathbf{Q}_n = \sigma_n^2 \mathbf{I}_M$ and the contribution $\mathbf{Q}_I$ from the N_I out-of-cell active interferers. We assume that the signal from each interferer SS_i , placed in the spatial location s_i within the i^{th} cell, with $i=1, \dots, N_I$, is received by BS_0 through a multipath channel with the same characteristics as in (7). It follows that the i^{th} interferer spatial covariance (averaged with respect to fast fading) depends on the DOA's $\{\theta_{i,r}(s_i)\}_{r=1}^{N_p}$, (evaluated with respect to the broadside) the normalized power-angle-profile $\{\Lambda_{i,r}(s_i)\}_{r=1}^{N_p}$ and the received power $\{P_{i0}^{(R)}(s_i)\}$ [dBm], according to:

$$\mathbf{Q}_I = \sum_{i=1}^{N_I} 10^{\frac{P_{i0}^{(R)}(s_i)}{20}} \sum_{r=1}^{N_p} \Lambda_{i,r}(s_i) \mathbf{a}(\theta_{i,r}(s_i)) \mathbf{a}^H(\theta_{i,r}(s_i)). \quad (11)$$

As in (8), the received power is obtained from the power $P_i^{(T)}$ transmitted by SS_i , taking into account the power loss due to propagation over the distance d_{i0} and the shadowing effect $S_{i0} \sim N(0, \sigma_s^2)$ over the link $SS_i - BS_0$:

$$P_{i0}^R(s_i) = P_i^T + G - L(d_{i0}) + S_{i0}. \quad (12)$$

Since adaptive modulation and coding is adopted to satisfy a fixed bit error rate ($BER = 10^{-6}$), the transmission mode selected (from those listed in **Table 1**) by the i^{th} user ($i \neq 0$) and the corresponding transmitted power will be functions of the path loss over the distance d_i and the shadowing over the link $SS_i - BS_i$. For a simple AWGN scenario (without shadowing), **fig.4** shows the transmission mode $T(d)$ (in dotted spaced scale) and the corresponding power $\bar{P}^{(T)}(d)$ required by a SS at distance d from its own BS. The power can be written as:

$$\bar{P}^{(T)}(d) = P_{\max}^{(T)} + 10\gamma \log\left(\frac{d}{d_{\max}(T(d))}\right) \quad (13)$$

where $d_{\max}(T)$ is the maximum distance at which the transmission mode T is supported. In our framework, the power transmitted by the i^{th} interferer has to be increased with respect to (13) to compensate the shadowing fluctuations $S_i \sim N(0, \sigma_s^2)$ among SS_i and BS_i . As this is possible only up to the maximum available power $P_{\max}^{(T)}$, we can equivalently write the transmitted power as:

$$P_i^{(T)} = \min\{\bar{P}^{(T)}(d_i) + S_i; P_{\max}^{(T)}\} \quad (14)$$

OPTIMIZATION OF THE SPACING BETWEEN THE RECEIVER ANTENNAS

[0026] In **fig.5** a possible interference scenario is based on planning Q4 (Q is meaning square cells and 4 is the frequency reuse factor). The considered BS₀ receives the useful signal from SS₀ and three first-ring interfering signals from SS₁, SS₂, and SS₃ located in the centre of their cells and transmitting on the same frequency as SS₀. The useful and interfering signals are transmitted with the following characteristics:

- Carrier frequency 3.5 GHz;
- Channel bandwidth 4 MHz;
- Number of subcarriers N = 256;
- Number of useful subcarriers N_U = 200;
- Channel length W (cyclic prefix length) = (32/N)×T_b, where T_b is the symbol duration;

[0027] To the only aim of simplifying the problem, the following assumptions are introduced:

- SS₀, SS₁, SS₂, and SS₃ have a single omnidirectional antenna;
- SS_i omnidirectional antenna gain = 2 dBi;
- BS₀ is equipped with an ULA of 4 antennas having 90° aperture;
- the wavefront impinging the BS₀'s array is supposed to be plane;
- BS₀ directional antenna gain = 16 dBi (broadside);
- the received signal is narrowband;
- the N_I interfering terminals are located in N_I fixed positions $\{s_i\}_{i=1}^{N_I}$ with main DOAs symmetric with respect to the broadside line: according to **fig.5** only three line-of-sight interferers are considered;
- null angular spread and fading for both useful and interferers;
- shadowing is not considered;
- fading uncorrelated over the subcarriers.

[0028] These simplifications shall be considered as an useful preliminary expedient to the only aim of introducing some theoretic arguments, but will be soon removed to achieve a better trade-off between beamforming and diversity. Successively, the channel and the interference will be modelled as said for expressions (7) and (11), and **Table 2 (APPENDIX A)**.

[0029] The spatial covariance expression (11) of the *i*th interferer includes N_p steering vectors **a**(θ_{*i,r*}(s_{*i*})) (N_p=1 under the above restrictive hypothesis), each of them denoting the response of receiving array to the direction of arrival θ_{*i,r*}(s_{*i*}). The response of the ULA illustrated in **fig.6** to the useful signal from SS₀ is:

$$\mathbf{a}(\theta_{0,r}) = \left[1, e^{j2\pi\frac{\Delta}{\lambda}\sin(\theta_{0,r})}, e^{j2\pi\frac{\Delta}{\lambda}\sin(\theta_{0,r})2}, \dots, e^{j2\pi\frac{\Delta}{\lambda}\sin(\theta_{0,r})(N_R-1)} \right]^T \quad (15)$$

where Δ is the spacing between adjacent antennas.

[0030] The response (15) is a spatial sinusoidal signal whose wave number is:

$$\omega_s = 2\pi\frac{\Delta}{\lambda}\sin(\theta_s). \quad (16)$$

[0031] The DOA of the interferer impinging on the array is thus discriminated without equivocation (alias), if for every angle θ_s a different wave number ω_s is obtained. The maximum admissible spacing Δ_{max} is the value which associates the greatest angular deviation θ_{max} in respect of the normal to the antennas' array at the Nyquist wave number. For every spacing Δ if the following bound is satisfied:

$$\Delta \leq \Delta_{\max} = \frac{\lambda}{2 \sin(\theta_{\max})} \quad (17)$$

the equivocation does not turn up. When the DOAs are unknown it shall suppose $\theta_{\max} = \frac{\pi}{2}$ and the corresponding

spacing is $\Delta = \frac{\lambda}{2}$, value that does not introduce alias for every DOA. For the examined planning covering a $\frac{\pi}{2}$

sector the maximum deviation from the normal is $\Delta\theta_{\max} = \frac{\pi}{4}$. From the equation (17): $\Delta_{\max} = \frac{\lambda}{\sqrt{2}} = 0.71\lambda$.

The angular resolution is proportional to the reciprocal of the length $L = N_R \Delta$ of the array. When $\Delta = \Delta_{\max}$ the incoming interfering signals are associated to distinct wave numbers maximally separated, for planning Q4 they are equal to ± 2.46 radian.

[0032] Let ω_i be the wave number of the signal coming from the generic subscriber station SS_i ; the (19) is:

$$\omega_i = 2\pi \frac{\Delta}{\lambda} \sin(\theta_i); \quad (18)$$

it is possible select Δ in a way that the wave numbers $\{\omega_i\}_{i=1,2,3}$ of the steering vectors in the direction of the interferers coming from $\{SS_i\}_{i=1,2,3}$ are coincident to each other. This happens when:

$$\Delta = \Delta_{opt} = \frac{n\lambda}{\sin(\Delta\theta)}, \quad \text{with } n = 1, 2, \dots \text{ (simplified to the only } n = 1) \quad (19)$$

where $\Delta\theta$ is the angular separation of the LOS interferers visible in **fig.5**. Being the (19) true, it results:

$$\omega_1 = \omega_2 = \omega_3 = 2\pi \frac{\Delta_{opt}}{\lambda} \sin(\theta_i) \quad (20)$$

and the three interferers are seen as superimposed by the array, so that a fictitious reduction of the interferers from three to one takes place. The angular separation is bound to 33.7° , limiting to $n=1$, $\Delta_{opt}=1.8\lambda$ is the best uniform spacing from (19). The length of a 4-element array for 3.5 GHz carrier used in WiMAX is 0.46 m ($\lambda=8.6$ cm). Shorter arrays more suitable for mobile applications are possible with highest carrier (WiMAX licensed bands cover up to 11 GHz). As known, a good suppression of the interference is achieved by placing at least a zero of the directivity function in correspondence of the direction of each interferer. In absence of alias three degrees of freedom (given by the number of antennas minus 1) are needed. In presence of alias only one degree of freedom is necessary, the remaining two can be used to superimpose two other zeros in the same direction of the first one, obtaining a larger attenuation.

[0033] The same considerations as for planning Q4 are extendible to other types of planning characterized by their parameters: AAP (Antenna Array Pattern), $\Delta\theta_{\max}$, $\Delta_{\max}$, $\Delta\theta$, and Δ_{opt} . Considering for example the planning Q1 (square cells with unitary reuse factor where the three interfering cells are adjacent to the considered one), it results:

$$AAP = \frac{1}{2} \pi, \quad \Delta\theta_{\max} = \frac{\pi}{4}, \quad \Delta_{\max} = 0.71\lambda, \quad \omega_s = \pm 2.46\pi, \quad \Delta\theta = 26.6^\circ, \quad \Delta_{opt} = n \cdot 2.24\lambda. \quad \text{Considering the planning E3 (Hex-}$$

agonal cells with reuse factor equal 3 and AAP = 120°), it results: $AAP = \frac{2}{3}\pi$ $\Delta\theta_{\max} = \frac{1}{3}\pi$, $\Delta_{\max} = 0.58\lambda$,

$\omega_s = \pm 2.61\pi$, $\Delta\theta = 46.10^\circ$, $\Delta_{\text{opt}} = n \cdot 1.39\lambda$. With certain types of planning, e.g. E1, the superimposition of the wave numbers $\{\omega_j\}_{j=1,2,3}$ can be incomplete; this is valid in general using arrays with limited length, in such a case the best uniform spacing Δ_{opt} is calculated minimizing the maximum number of the interferers distinguishable by the array.

[0034] Now the above limitations about the channel and the interference leading to the theoretical value Δ_{opt} are removed for extending the (19) to a more realistic value of the optimum separation. To this aim the ULA is momentarily maintained but the channel and the interference are characterized as previously said for respective equations (7) and (11) with further reference to the space-time variable fading parameters listed in **TABLE 2**.

[0035] When the initial restrictive hypotheses are neglected, to say when: A) all terminals regulate the transmission power according to an adaptive modulation, based on the channel state, so as to satisfy a fixed bit error rate (BER = 10⁻⁶); B) the channel gathering the complex gains from the N_R receiving antennas is modelled by means of a space-time multipath propagation, characterized by angular-delay dispersion; C) fast-fading and shadowing power fluctuations are considered; D) path-loss attenuation conforming for example the Hata-Okomura model is taken into account; E) terminals are randomly distributed within their respective cells, the optimal spacing Δ_{opt} is calculable as the spacing that minimizes the spread between the N_I wave numbers associated to the barycentric DOAs of the N_I interfering cells. The i^{th} barycentric DOA refers to the i^{th} interfering cell, with $i=1, \dots, N_I$, and it is calculated from the power-angle profile of the channel between the interfering station located in the i^{th} cell and the receiving station located in the cell of interest, when the spatial location of the interfering station is randomly distributed within its cell. Assuming a multipath channel with an arbitrary number of paths N_p , the i^{th} barycentric DOA is calculated by executing a weighted average extended to the $N_p \times S$ directions of arrival of the N_p paths by the S points of a grid indicative of the positions spanned by the i^{th} interfering station inside its cell, weighting each DOA by the power received on that path.

[0036] The following is a down-top description of the operations said above, starting from the calculation of the barycentric DOAs. Accordingly, the multipath generated by the i^{th} interferer station ideally collapses in a single path characterized by a barycentric DOA θ_i^B :

$$\theta_i^B = \frac{\sum_{s=1}^S 10^{\frac{P_{i,0}^{(R)}(s)}{10}} \sum_{r=1}^{N_p} \Lambda_{i,r}(s) \theta_{i,r}(s)}{\sum_{s=1}^S 10^{\frac{P_{i,0}^{(R)}(s)}{10}}} \quad (21)$$

and a barycentric received power P_i^B :

$$P_i^B = \frac{1}{S} \sum_{s=1}^S 10^{\frac{P_{i,0}^{(R)}(s)}{10}} \quad (22)$$

[0037] Term barycentric is appropriate indeed because of the strict resemblance between the (21) with the mathematical formula used to calculate the barycentric position of an ensemble of material points distributed as the S iterated multipath. Introducing θ_i^B (21) in the (18) we obtain the barycentric wave number ω_i^B :

$$\omega_i^B = 2\pi \frac{\Delta}{\lambda} \sin(\theta_i^B). \quad (23)$$

[0038] For a generic cellular planning, the optimal spacings for the ULA case can be found by minimizing the spread of the barycentric wave numbers weighted with respect to the barycentric received powers, therefore it is the solution to the following problem:

$$\Delta_{opt} = \arg \min_{\Delta} \sum_{i=1}^{N_I} \left(\omega_i^B(\Delta) - \bar{\omega}^B(\Delta) \right)^2 P_i^B \quad (24)$$

where: $\omega_i^B(\Delta)$ (the objective function) is the wave number associated to the i^{th} barycentric DOA as a function of the spacing Δ , and

$$\bar{\omega}^B(\Delta) = \frac{\sum_{i=1}^{N_I} \omega_i^B(\Delta) P_i^B}{\sum_{i=1}^{N_I} P_i^B} \quad (25)$$

is the weighted average wave number.

[0039] Closed form solution can be dealt with when considering a planning with N_I interfering cells with non-negligible received interference power coming from the broadside: by defining a weighted average barycentric DOAs separation $\Delta\theta^B$ as:

$$\Delta\theta^B = \frac{\sum_{i=2}^{N_I} P_i^B \theta_i^B}{\sum_{i=2}^{N_I} P_i^B} \quad (26)$$

For $N_I = 3$:

$$\Delta\theta^B = \frac{P_2^B \theta_2^B + P_3^B \theta_3^B}{P_2^B + P_3^B} \quad (27)$$

where interfering cell for $i=1$ is in broadside direction. The (26) and (27) are right in all effects because of the symmetry of the main DOAs with respect to the broadside $\theta_{BS} = 0$ degrees and the fact they are evaluated with respect to the

broadside, so that it results $\Delta\theta_i^B = \theta_i^B - \theta_{BS} = \theta_i^B$.

The final optimum spacing reads:

$$\Delta_{opt} = \frac{\lambda}{\sin(\Delta\theta^B)} \quad (28)$$

[0040] The value $\Delta_{opt}=1.8\lambda$ is substantially confirmed by the unrestricted approach as a good trade-off between

beamforming and diversity. The following wave numbers $\omega_i^B = 2\pi \frac{\Delta_{opt}}{\lambda} \sin(\theta_i^B)$ of the steering vectors of the

array in the barycentric directions θ_i^B are coincident to each other, so that the maximum number of barycentric interferers distinguishable by the array is minimized.

[0041] Although the invention has been described with particular reference to a preferred embodiment, it will be evident to those skilled in the art, that the present invention is not limited thereto, but further variations and modifications may be applied without departing from the scope thereof. For example, expressions equivalent to the (19) valid for the ULA are easily obtainable for different arrays with equally spaced antennas arranged according to other geometrical shapes, for example circular, on the basis on the best suitability to cope with the cellular scenario.

APPENDIX A

TABLE 1
Transmission modes and corresponding SNR operative threshold with $\text{BER} = 10^{-6}$
with fading uncorrelated over subcarriers

TX Mode	Modulation	Coding rate	R_b [Mbit/s]	SNR [dB] @BER= 10^{-6}
T ₁	BPSK	1/2	1.2	5.6
T ₂	QPSK	1/2	2.6	11.2
T ₃	QPSK	3/4	3.9	18.5
T ₄	16-QAM	1/2	5.2	17.0
T ₅	16-QAM	3/4	7.9	25.2
T ₆	64-QAM	2/3	10.8	25.8
T ₇	64-QAM	3/4	11.9	30.5

TABLE 2
Further Q4 planning parameters for the evaluation of the average SINR

Parameter	Value	Description
N_I	3	Number of potential interferers
N_p	3	Number of rays (paths) for interferer i^{th}
σ_θ^0	6°	standard deviation of the DOA from SS ₀
σ_θ^i	2°	standard deviation of the DOA from interferers $\{SS_i\}_{i=1,2,3}$
τ_r	μs	Delay on the r^{th} ray (according to SUI-4 channel model)
P_r	dB	Power attenuation on the r^{th} ray (according to SUI-4 channel model)
<i>Square cell side</i>	1000 m	Dimension of the cell
<i>Grid size</i>	50 m	Positions of the transmitter inside the cell

USED ACRONYMS

AAP	- Antenna Array Aperture
AWGN	- Additive White Gaussian Noise
DFT	- Discrete Fourier Transform
DOA	- Direction Of Arrival
ETSI	- European Telecommunications Standards Institute
IEEE	- Institute of Electrical and Electronics Engineers
LOS	- Line Of Sight
LS	- Least Squares
MAN	- Metropolitan Area Networks
MAP	- Maximum a Posteriori
MDL	- Minimum Description Length
MIMO	- Multiple Input Multiple Output
MRC	- Maximum Ratio Combining
MSE	- Mean Square Error
MVDR	- Minimum Variance Distortionless Response
NLOS	- Not Line Of Sight
OFDM	- Orthogonal Frequency Division Multiplexing
OFDMA	- Orthogonal Frequency Division Multiplex Access
SDMA	- Space Division Multiple Access
SIMO	- Single Input Multiple Output
SINR	- Signal to Interference and Noise Ratio
SNR	- Signal to Noise Ratio
SUI	- Stanford University Interim
TDMA	- Time Division Multiple Access
ULA	- Uniform Linear Array
WiMAX	- Worldwide Interoperability for Microwave Access

Claims

1. Method for optimizing the spacing between uniformly spaced antennas of an array usable by the receiving stations, either fixed or mobile, of a cellular telecommunications network where under the restrictive hypothesis of disregarding the angular power spread along the multipath the optimal spacing is calculable in closed form by the following ideal

expression: $\Delta_{opt} = \frac{\lambda}{\sin(\Delta\theta)}$ leading to the superimposition of the interferers as seen by the array, being λ

the wavelength of the carrier and $\Delta\theta$ the angular separation of the fixed interferers, **characterized in that** includes the following step;

- replacing said $\Delta\theta$ with the weighted average $\Delta\theta^B$ of the angular separations $\Delta\theta_i^B$ between adjacent barycentric direction of arrivals θ_i^B of N_I spatial power distributions generated by N_I interferer stations (SS₁, SS₂, SS₃) located inside respective cells, being the direction θ_i^B calculated from the assumed cellular planning and the assumed channel model.

2. The method of claim 1, **characterized in that** said barycentric direction of arrival θ_i^B is calculated for each i^{th} interferer station executing a weighted average extended to the $N_p \times S$ directions of arrival $\theta_{i,r}(s)$ evaluated with respect to the normal of the array of the N_p rays r characterizing the multipath by the S points s of a grid indicative of the positions spanned by the i^{th} interfering station inside its cell.

3. The method of claim 2, **characterized in that** the weight used for averaging a direction of arrival $\theta_{i,r}(s)$ is the power $\Lambda_{i,r}(s) \cdot 10^{\frac{P_{i,0}^{(R)}(s)}{10}}$ at the receiving station along said direction $\theta_{i,r}(s)$, where $\Lambda_{i,r}(s)$ is the normalized power density along the r direction.

4. The method of claim 3, **characterized in that** said barycentric direction of arrival θ_i^B is calculated according to the following expression:

$$\theta_i^B = \frac{\sum_{s=1}^S 10^{\frac{P_{i,0}^{(R)}(s)}{10}} \sum_{r=1}^{N_p} \Lambda_{i,r}(s) \theta_{i,r}(s)}{\sum_{s=1}^S 10^{\frac{P_{i,0}^{(R)}(s)}{10}}}$$

the denominator indicating a barycentric received power P_i^B multiplied by S .

5. The method of claim 4, **characterized in that** said angular separation $\Delta\theta^B$ is calculated for a specific cellular planning with N_I interfering cells by defining a weighted average barycentric DOA separation $\Delta\theta^B$ as:

$$\Delta\theta^B = \frac{\sum_{i=2}^{N_I} P_i^B \theta_i^B}{\sum_{i=2}^{N_I} P_i^B}$$

where interfering cell for $i = 1$ is in broadside direction $\theta_{BS} = 0$ degrees, and $\Delta\theta_i^B = \theta_i^B - \theta_{BS} = \theta_i^B$ is referred to the broadside.

6. The method of any claim 1 to 5, **characterized in that** in correspondence of said optimal spacing Δ_{opt} the barycentric wave numbers:

$$\omega_i^B = 2\pi \frac{\Delta_{opt}}{\lambda} \sin(\theta_i^B), \quad \text{for } i = 1, \dots, N_I$$

of the directivity function of the array in the barycentric directions θ_i^B are coincident to each other, so that the maximum number of barycentric interferers distinguishable by the array is minimized.

7. The method of any claim 1 to 6, **characterized in that** in a scenario with square cell planning and the interfering stations placed inside the first interfering ring, the value of said optimum spacing is $\Delta_{opt} = 1.8\lambda$, as an optimum trade-off between beamforming and space diversity.

8. The method of claim 1, **characterized in that** said optimal spacing is equivalent to minimize the spread of the barycentric wave numbers weighted with respect to the barycentric received powers.

9. The method of claim 8, **characterized in that** the minimization problem can be set as:

$$\Delta_{opt} = \arg \min_{\Delta} \sum_{i=1}^{N_I} \left(\omega_i^B(\Delta) - \bar{\omega}^B(\Delta) \right)^2 P_i^B, \quad \text{where } \omega_i^B(\Delta) \text{ is the wave number associated to the } i^{th}$$

barycentric DOA as a function of the spacing Δ , and $\bar{\omega}^B(\Delta) = \frac{\sum_{i=1}^{N_I} \omega_i^B(\Delta) P_i^B}{\sum_{i=1}^{N_I} P_i^B}$ is the weighted average wave

number.

WiMAX 802.16-2004 OFDM-TDMA FRAME FOR UPLINK FIXED ACCESS

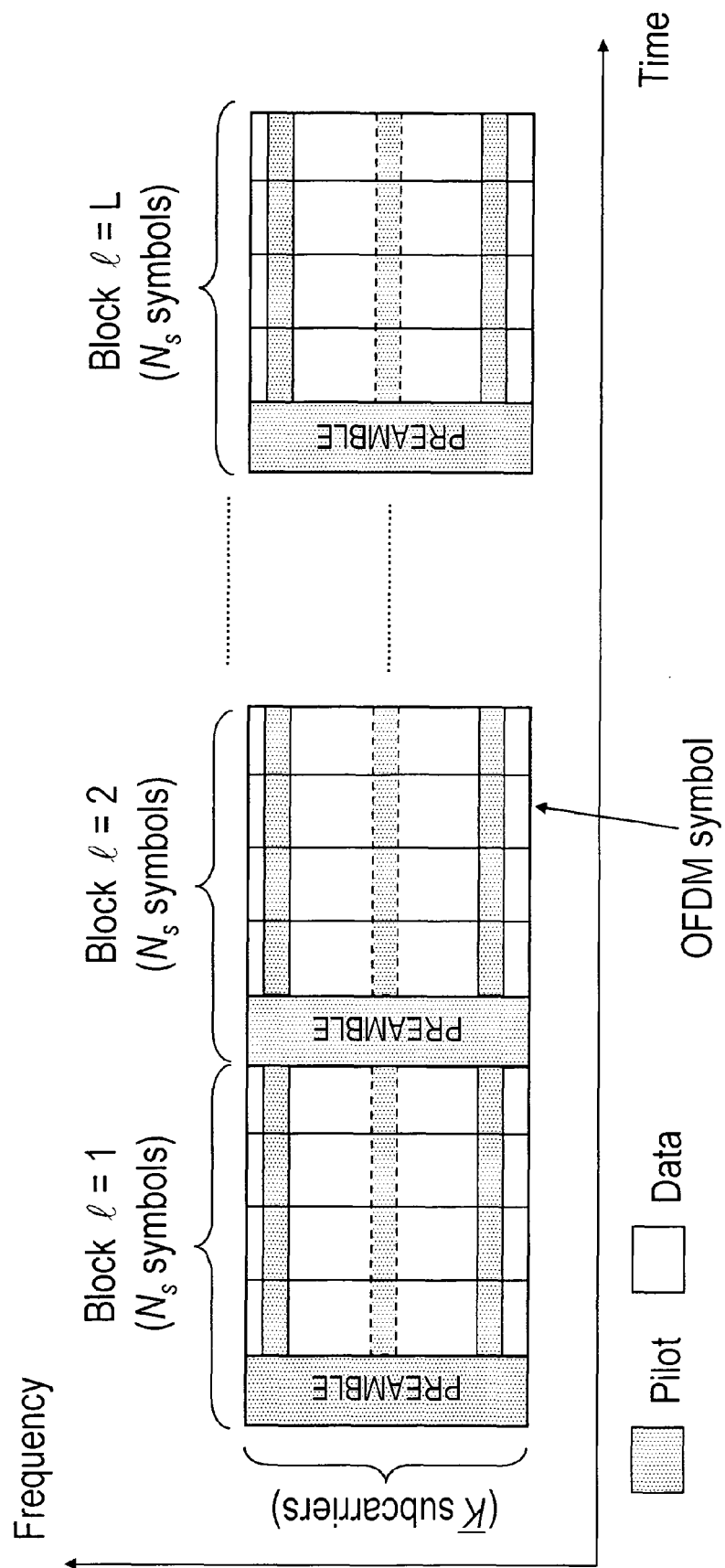
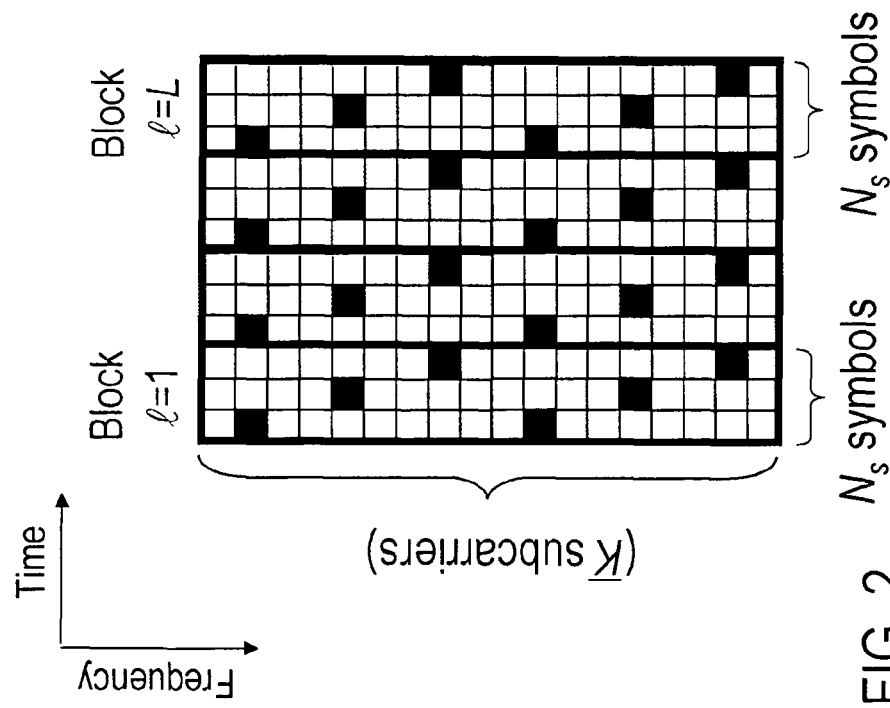
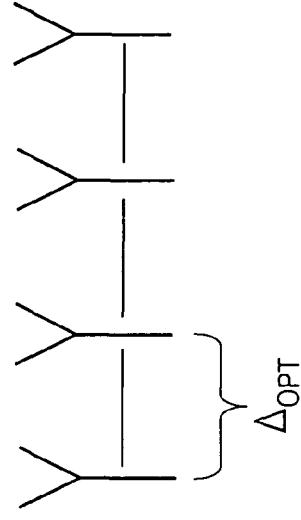


FIG. 1

WiMAX 802.16-e OFDMA-TDMA FRAME FOR UPLINK ACCESS



OPTIMALLY SPACED UNIFORM ARRAY FOR Q4 PLANNING



RECEPTION DISTURBED BY THREE UPLINK INTERFERERS

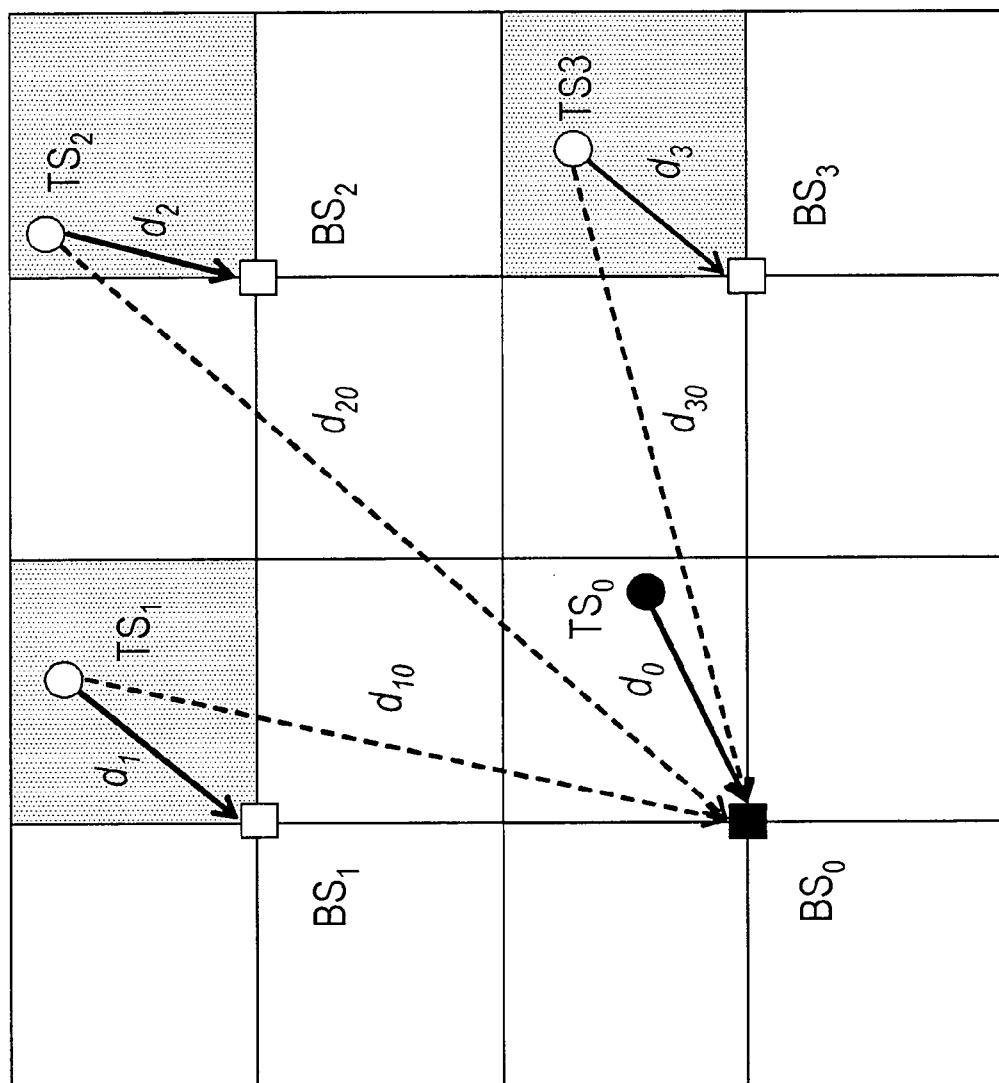


FIG. 3

Calculation of the power $\widetilde{P}_i^{(T)}$ radiated by the i^{th} interferer

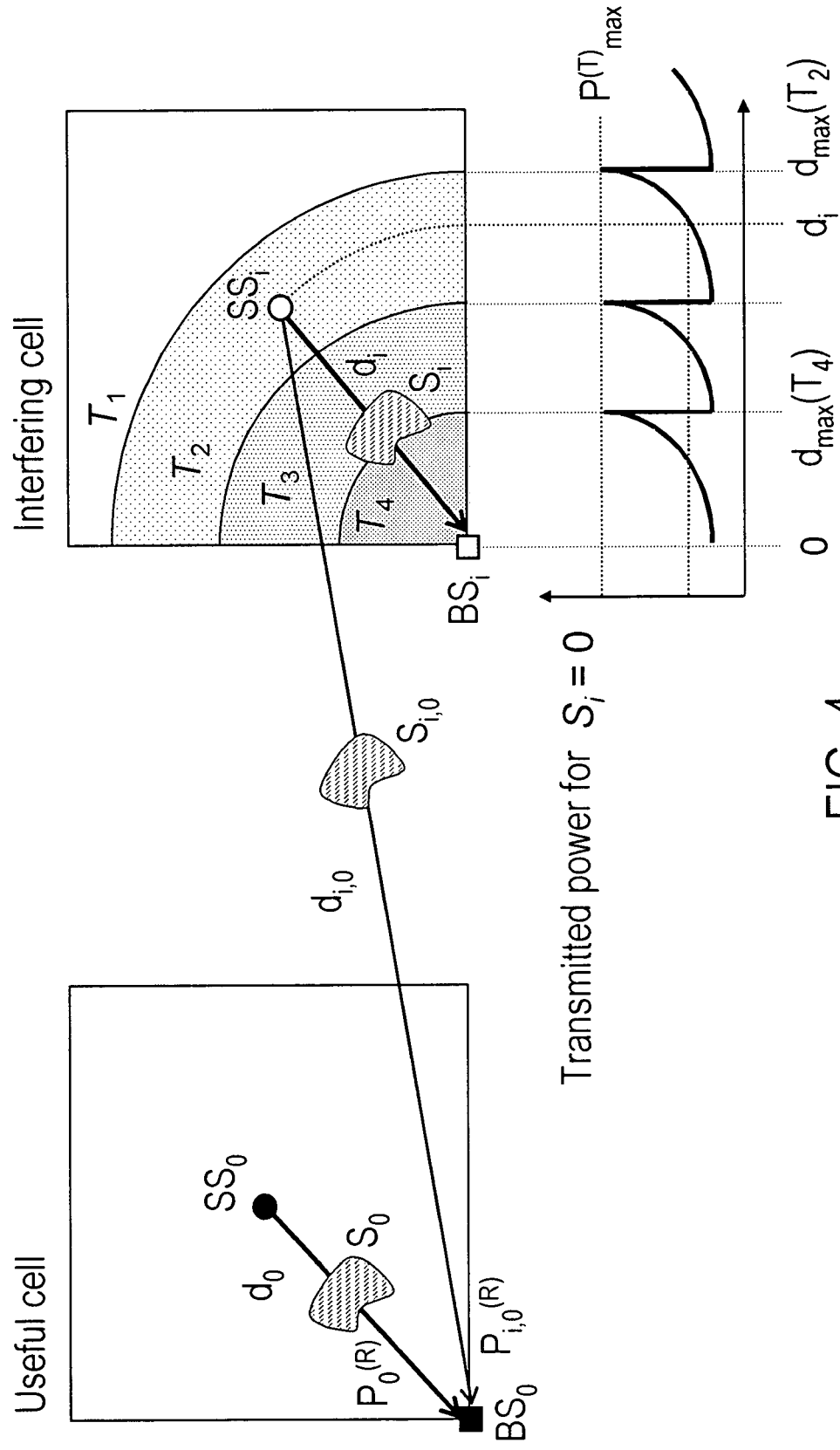


FIG. 4

Q4 PLANNING - FIRST INTERFERER RING

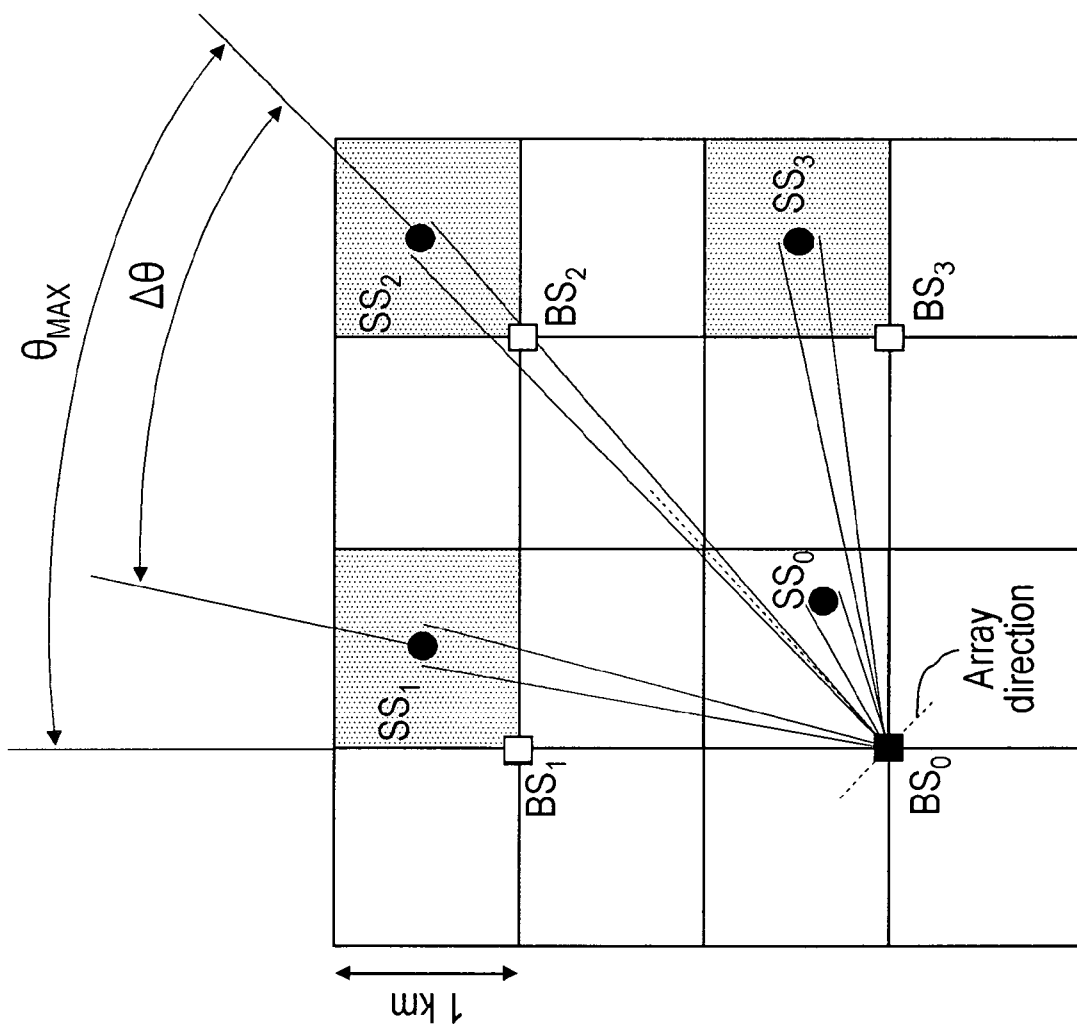


FIG. 5



European Patent
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EUROPEAN SEARCH REPORT

Application Number
EP 06 42 5093

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
D,A	"Optimal design of linear arrays in a TDMA cellular system with Gaussian interference" SIGNAL PROCESSING ADVANCES IN WIRELESS COMMUNICATIONS, 2005 IEEE 6TH WORKSHOP ON NEW YORK, NY, USA JUNE 2-8, 2005, PISCATAWAY, NJ, USA, IEEE, 2 June 2005 (2005-06-02), pages 485-489, XP010834466 ISBN: 0-7803-8867-4 * the whole document *	1-9	INV. H01Q21/08 H01Q21/22
A	US 6 056 780 A (AUBRY ET AL) 2 May 2000 (2000-05-02) * column 1, line 46 - column 2, line 62; figures 1-4 *	1	
A	EP 0 755 090 A (NORTEL NETWORKS CORPORATION; NORTEL NETWORKS LIMITED) 22 January 1997 (1997-01-22) * figure 2 *	1	
A	US 2005/001765 A1 (RYU KIL-HYEN ET AL) 6 January 2005 (2005-01-06) * figures 1-5 *	1	
			TECHNICAL FIELDS SEARCHED (IPC)
			H01Q H04B H04Q
The present search report has been drawn up for all claims			
Place of search The Hague		Date of completion of the search 3 August 2006	Examiner Angrabeit, F
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1
EPO FORM 1503 03.82 (P04C01)

**ANNEX TO THE EUROPEAN SEARCH REPORT
ON EUROPEAN PATENT APPLICATION NO.**

EP 06 42 5093

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
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03-08-2006

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 6056780	A	02-05-2000	DE 69726083 D1	18-12-2003
			DE 69726083 T2	26-08-2004
			EP 0831554 A1	25-03-1998
			FR 2753798 A1	27-03-1998

EP 0755090	A	22-01-1997	DE 69618394 D1	14-02-2002
			DE 69618394 T2	14-11-2002
			US 5778324 A	07-07-1998

US 2005001765	A1	06-01-2005	JP 2005027268 A	27-01-2005
			TW 220598 B	21-08-2004

REFERENCES CITED IN THE DESCRIPTION

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Non-patent literature cited in the description

- **S. SAVAZZI ; O. SIMEONE ; U. SPAGNOLINI.** Optimal design of linear arrays in a TDMA cellular system with Gaussian interference. *IEEE Proc. SPAWC*, 2005 [0005]