



(51) International Patent Classification:
H01Q 3/36 (2006.01) *H01Q 3/26* (2006.01)
G01S 3/42 (2006.01)

(21) International Application Number:
PCT/AU2010/000091

(22) International Filing Date:
29 January 2010 (29.01.2010)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
2009900371 2 February 2009 (02.02.2009) AU

(71) Applicant (for all designated States except US): **COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION** [AU/AU]; Limestone Avenue, Campbell, ACT 2612 (AU).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **GUO, Yingjie, Jay** [GB/AU]; 77 Pennant Parade, Epping, NSW 2121 (AU). **BUNTON, John, David** [AU/AU]; 15 Hourglass Glade, St Clair, NSW 2759 (AU). **DYADYUK, Valeriy** [AU/AU]; 1/40 Waters Road, Cremorne, NSW 2090 (AU). **HUANG, Xiaojing** [AU/AU]; 24 Cave Avenue, North Ryde, NSW 2113 (AU).

(74) Agent: **SPRUSON & FERGUSON**; GPO Box 3898, Sydney, NSW 2001 (AU).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: HYBRID ADAPTIVE ANTENNA ARRAY

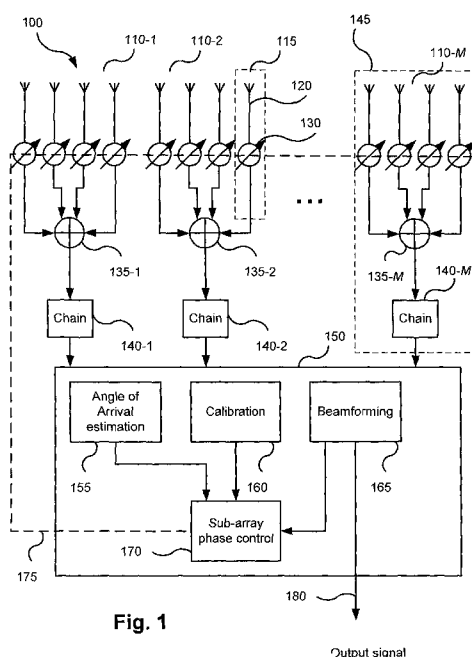


Fig. 1

(57) Abstract: Disclosed is a hybrid antenna array (100) comprising a plurality of digital branches (145), each digital branch including an analogue beamforming sub-array (e.g. 110-1), each sub-array having a plurality of antenna elements (120), a phase shifter (130) adapted to apply a phase shift to the signal from each antenna element, and a combiner (e.g. 135-1) adapted to combine the phase-shifted signals. Each digital branch also includes a signal chain (e.g. 140-1) adapted to convert the output of the sub-array to baseband. The hybrid antenna array also comprises a digital processing module (150), including: an angle of arrival estimation sub-module (155) adapted to estimate an angle of arrival of a signal at the antenna elements; a phase control sub-module (170) adapted to control the phase shift applied by each phase shifter depending on the estimated angle of arrival; and a digital beamformer (165) adapted to combine the baseband signals from the digital branches using a weight vector to form an output signal (180).

HYBRID ADAPTIVE ANTENNA ARRAY

Technical Field

The present invention relates generally to antenna design and, in particular, to architectures and methods for adaptive antenna arrays.

5

Background

Adaptive antennas are important subsystems for long range, mobile and *ad hoc* wireless communications and sensing networks. The most powerful adaptive antenna architecture is the digital beamforming array, where each antenna element has an associated signal chain to convert the received signal from RF (radio frequency) to baseband, and the baseband signals are processed by a digital beamformer using adaptive filtering techniques. Digital beamforming antenna arrays have the capability of generating many antenna patterns simultaneously, performing high precision beamforming such as nulling, and producing output signals with the maximum signal to noise and interference ratio (SNIR). A further advantage of the digital beamforming array architecture is that on-line calibration of different branches can be handled automatically by the digital beamformer. However, purely digital beamforming antenna arrays do have a major disadvantage. Since the cost of processing digital data is proportional to the bandwidth and the computational power required for digital signal processing increases at least linearly with the number of elements, a large digitally beamformed antenna array for wideband operation is simply too costly and impractical for most applications. Another problem with digital beamforming arrays is that, due to the limitation of physical space defined by the array element spacing, a pure digital beamformer is impractical at millimetre-wave frequencies beyond approximately 55 GHz. The element spacing required for suppression of grating lobes at scan angles within 60 degrees is limited to 2.9

10

15

20

and 1.7 mm at operating frequencies of 55 and 95 GHz respectively, thus making it extremely difficult to physically place the signal chains behind the antenna elements.

The other principal adaptive array architecture is the analogue beamformer, in which “smart beams” are formed using RF or IF phase shifters on each antenna element in the array. In purely analogue systems, cost is a very weak function of bandwidth. Thus, for wideband adaptive antenna systems with a large number of elements, an analogue adaptive antenna array is much more economical than a purely digital adaptive array. However, an analogue beamformer has certain disadvantages. First, the calibration of a large analogue array is labour-intensive and on-line recalibration is extremely difficult. Second, special means must be employed for beam tracking, thus increasing the complexity and the cost. Third, there is no access to the baseband signals of individual analogue branches because the phase-shifted IF or RF signals are combined before conversion to baseband, so the capacity to form selective beam patterns is limited. These problems are particularly severe for large analogue arrays where the imperfection and ageing of components can cause serious degradation in antenna performance.

Summary

Disclosed are arrangements which seek to ameliorate the above disadvantages by means of a hybrid adaptive antenna array, which comprises an array of antenna elements partitioned into multiple analogue beamforming sub-arrays and a digital beamformer on the sub-array outputs, with a control path back to the analogue phase shifters. This reduces the size of the digital beamformer by a factor equal to the average number of elements in each sub-array. Also disclosed are calibration methods for both the analogue and the digital beamformers in the hybrid adaptive array. In addition, disclosed are search and tracking methods for the hybrid adaptive array. The disclosed hybrid array provides an

efficient means of producing large, high-gain adaptive antenna arrays at relatively low cost.

According to a first aspect of the present disclosure, there is provided a hybrid antenna array comprising:

- 5 (a) a plurality of digital branches, each digital branch including:
 - (i) an analogue beamforming sub-array, each sub-array having a plurality of antenna elements, a phase shifter adapted to apply a phase shift to the signal from each antenna element, and a combiner adapted to combine the phase-shifted signals;
 - (ii) a signal chain adapted to convert the output of the sub-array to
10 baseband; and
- (b) a digital processing module, including:
 - (i) an angle of arrival estimation sub-module adapted to estimate an angle of arrival of a signal at the antenna elements;
 - (ii) a phase control sub-module adapted to control the phase shift
15 applied by each phase shifter depending on the estimated angle of arrival; and
 - (iii) a digital beamformer adapted to combine the baseband signals from the digital branches using a weight vector to form an output signal.

According to a second aspect of the present disclosure, there is provided a method of estimating the angle of arrival of a signal at an antenna array comprising a plurality of
20 digital branches and a digital beamformer, the method comprising:

- (a) cross-correlating the baseband signals from adjacent digital branches;
- (b) for a plurality of candidate beams,
 - (i) setting the phase shifts using the arguments of the cross-correlation values; and

(ii) computing the power of the output signal of the digital beamformer;

(c) determining the candidate beam giving the maximum output power; and

(d) estimating the angle of arrival from the cross-correlation values of the
5 determined candidate beam.

According to a third aspect of the present disclosure, there is provided a method of calibrating an antenna array comprising a plurality of digital branches and a digital beamformer, the method comprising:

(a) estimating the expected phase difference between the baseband signals
10 from adjacent digital branches;

(b) determining the phase deviation of each digital branch as the difference between the expected phase difference and an actual phase difference between the baseband signals from a digital branch and an adjacent previously calibrated digital branch; and

(c) applying each phase deviation to the baseband signal from the
15 corresponding digital branch.

According to a fourth aspect of the present disclosure, there is provided a method of calibrating an antenna array comprising a plurality of analogue branches, each analogue branch comprising an antenna element and a phase shifter, the method comprising:

(a) optimising the phase shifts applied by the phase shifters to an input signal
20 to the array so as to obtain a maximum-power output signal from the array;

(b) determining expected values of the phase shifts using an angle of arrival of the input signal;

(c) determining the phase deviation for each analogue branch in the array as the difference between the expected phase shift and the optimised phase shift for the analogue branch; and

(d) applying each phase deviation to adjust the phase shift applied by the
5 corresponding phase shifter.

Brief Description of the Drawings

In the drawings:

Fig. 1 shows a receiving hybrid antenna array according to one embodiment of the
10 present invention;

Fig. 2a shows an exemplary linear configuration of the hybrid array of Fig. 1;

Fig. 2b shows an exemplary planar configuration of the hybrid array of Fig. 1; and

Fig. 3 is a flowchart illustrating a method of estimating the angle of arrival carried
out by the hybrid antenna array of Fig. 1.

15

Detailed Description

Where reference is made in any one or more of the accompanying drawings to steps and/or features, which have the same reference numerals, those steps and/or features have for the purposes of this description the same function(s) or operation(s), unless the
20 contrary intention appears.

Fig. 1 shows a receiving hybrid antenna array 100 according to one embodiment. The antenna elements, e.g. 120, in the array 100 are grouped into M analogue beamforming sub-arrays 110-1, 110-2, ..., 110- M .

A hybrid array is said to have a planar configuration (a planar array) if all the sub-arrays are located in a single plane. A linear configuration (a linear array) is a special case of a planar configuration in which all the sub-arrays are located in a single line.

Fig. 2a shows an exemplary linear configuration 200 of the hybrid antenna array 100 of Fig. 1. The exemplary linear array 200 comprises two sub-arrays 210-1 and 210-2 arranged side-by-side, each sub-array 210-*m* comprising four evenly-spaced elements, e.g. 220, arranged in a straight line. Fig. 2b shows an exemplary planar configuration 230 of the hybrid antenna array 100 of Fig. 1. The exemplary planar array 230 comprises sub-arrays 240-1, 240-2, 240-3, and 240-4 laid out in a square, each sub-array 240-*m* comprising a four-by-four square grid of elements, e.g. 250. The hatching of each element 250 indicates the sub-array to which it belongs.

Each sub-array 110-*m* in Fig. 1 is illustrated with 4 elements 120, which is the preferred sub-array size for a linear array, while the preferred sub-array size for a planar array is 4 by 4 elements. In general, different sub-arrays may have different numbers of elements.

A planar array is defined as uniformly spaced if the number *M* of sub-arrays can be expressed as $M = M_x \times M_y$, where M_x and M_y are the numbers of sub-arrays arranged along the x-axis and the y-axis respectively. The *i*-th element in sub-array *m* of a uniformly spaced planar array is located at coordinates $(X_{i,m}, Y_{i,m})$ such that

$$\begin{aligned} X_{i,m} &= X_i + m_x d_x^{(s)}, & m_x &= 0, 1, \dots, M_x - 1 \\ Y_{i,m} &= Y_i + m_y d_y^{(s)}, & m_y &= 0, 1, \dots, M_y - 1 \end{aligned}$$

where $m = m_y M_x + m_x$, $d_x^{(s)}$ and $d_y^{(s)}$ are the horizontal and vertical spacings of the sub-arrays respectively, and (X_i, Y_i) is the location of the *i*-th element of the sub-array

- 7 -

numbered $m = 0$. For example, the planar array 230 is uniformly spaced with $M_x = M_y = 2$ and $d_x^{(s)} = d_y^{(s)}$.

A uniformly spaced linear array is a special case of a uniformly spaced planar array with $M_y = 1$, so $M_x = M$, $m_y = 0$, and $Y_{i,m} = Y_i$ ($d_y^{(s)}$ is irrelevant). For example, the
 5 linear array 200 is uniformly spaced with $M_x = 2$ and $M_y = 1$.

A rectangular sub-array has $N = N_x \times N_y$ elements, where N_x and N_y are the numbers of elements arranged along the x-axis and the y-axis respectively. The location (X_i, Y_i) of the i -th element of the rectangular sub-array numbered $m = 0$ is given by

$$\begin{aligned} X_i &= X_0 + i_x d_x^{(e)}, & i_x &= 0, 1, \dots, N_x - 1 \\ Y_i &= Y_0 + i_y d_y^{(e)}, & i_y &= 0, 1, \dots, N_y - 1 \end{aligned}$$

where $i = i_y N_x + i_x$, $d_y^{(e)}$ and $d_x^{(e)}$ are the element spacings along the y-axis and x-axis respectively, and (X_0, Y_0) is the location of the element numbered 0. For example, each sub-array 240- m in the planar array 230 is rectangular, with $N_x = N_y = 4$ and $d_x^{(e)} = d_y^{(e)}$.

A linear sub-array is a special case of a rectangular sub-array with $N_y = 1$, so $N_x =$
 15 N , $i_y = 0$, and $Y_i = Y_0$ for all i ($d_y^{(e)}$ is irrelevant). For example, each sub-array 210- m in the linear array 200 is linear, with $N_x = 4$.

The planar array 230 is a uniformly spaced planar array comprising rectangular sub-arrays with $d_x^{(s)} = N_x d_x^{(e)}$ and $d_y^{(s)} = N_y d_y^{(e)}$. The linear array 200 is also uniformly spaced, comprising linear sub-arrays with $d_x^{(s)} = N_x d_x^{(e)}$.

20 Each antenna element 120 belongs to an analogue signal branch, e.g. 115, which also includes a phase shifter, e.g. 130, which is independently controllable by an external signal 175, as described below. The phase shifter 130 alters the phase of the received signal from the antenna element 120 by a controllable amount. Each analogue branch 115

may also contain a low noise amplifier, an attenuator, a filter, and a frequency down-converter, using a local oscillator, to intermediate frequency (not shown). The phase shifter 130 is preferably implemented as a controllable or 'switched' delay in the radio frequency (RF) signal, the down-converted intermediate frequency (IF) signal, or the local
5 oscillator.

The outputs of each analogue branch 115 in the sub-array 110-*m* are combined by a combiner 135-*m*. The phases of each phase shifter 130 are controlled as described below such that each sub-array 110-*m* generates a beam in a desired direction, for example the angle of arrival of the RF signal incident on the hybrid array 100. The combination of RF
10 signals from different analogue branches by the combiner 135-*m* is preferably implemented by a conventional corporate network.

In alternative embodiments, the analogue beamforming in a sub-array 110-*m* is performed by a Rotman lens or a Butler matrix rather than a phased array as described above.

15 The output of each sub-array 110-*m* is passed to a chain 140-*m*, which converts the RF or IF signal to baseband. The combination, e.g. 145, of a sub-array 110-*m* and a chain 140-*m* is referred to herein as a "digital branch". The *M* baseband signals from the digital branches 145 are processed in a digital processing module 150 comprising several sub-modules: a digital beamformer 165, a calibration sub-module 160, an angle of arrival
20 estimation sub-module 155, and a sub-array phase control sub-module 170. The operation of each sub-module will be described below.

The digital processing module 150 serves several purposes. First, the digital beamformer 165 ensures that the output signal 180 of the hybrid array 100 has a highest signal to noise and interference ratio (SNIR). Second, the digital processing module 150,
25 through the sub-array phase control sub-module 170, provides the control signal 175 for

each phase shifter 130 in each sub-array 110- m . The angle of arrival estimation sub-module 155 plays a role in this function, as described below. Third, the digital processing module 150, through the calibration sub-module 160, provides calibration both for the digital branches 145 and for each analogue branch 115 in the hybrid array 100 as described
 5 below. The preferred implementations for the digital signal processing module 150 are embedded firmware on Field Programmable Gate Arrays (FPGAs) or a dedicated ASIC, which is more suitable for mass production.

The digital beamformer 165 generates an output signal $z(n)$ 180 at time n by applying weights $\mathbf{w}(n) = [w_0(n) \ w_1(n) \ \cdots \ w_{M-1}(n)]^T$ to the (complex-valued) baseband
 10 signal vector $\mathbf{x}(n) = [x_0(n) \ x_1(n) \ \cdots \ x_{M-1}(n)]^T$ output by the digital branches 145 as follows:

$$z(n) = \mathbf{w}^H(n) \mathbf{x}(n) \quad (1)$$

where H indicates the conjugate transpose of a vector.

Forming the digital beam

15 The weights $\mathbf{w}(n)$ vary or adapt with time to cope with changing signal and / or system characteristics. There are a number of adaptive algorithms such as the least mean squares (LMS) algorithm and the recursive least squares (RLS) algorithm which can be employed to update the weight vector in a conventional digital beamformer. The method used by the digital beamformer 165 according to one embodiment uses a reference signal
 20 $s(n)$ that was known to have been transmitted to arrive at time n . This knowledge is available during a training period for the hybrid array 100. The reference signal could be the header portion of a data packet. According to this embodiment, the digital beamformer 165 iteratively adjusts the weight vector as follows:

$$\mathbf{w}(n) = \alpha \mathbf{w}(n-1) + (1 - \alpha) s^*(n) \mathbf{x}(n) \quad (2)$$

where α is a “forgetting factor” that controls the effective window size of the time averaging, and the * superscript indicates complex conjugation.

In an alternative embodiment, to reduce the sensitivity of the digital beamformer to the magnitude of the input signal vector $\mathbf{x}(n)$, the input signal vector $\mathbf{x}(n)$ is normalized, resulting in the following iterative adjustment equation:

$$\mathbf{w}(n) = \alpha \mathbf{w}(n-1) + (1 - \alpha) s^*(n) \frac{\mathbf{x}(n)}{\|\mathbf{x}(n)\|^2} \quad (3)$$

For slow moving targets, the weights $\mathbf{w}$ can be fixed after the training period until the next training period (periodic adaptation). For fast moving target, after the training period, the output signal $z(n)$ can be used as the reference signal $s(n)$ (known as decision-aided beamforming).

Estimating the angle of arrival from the weights

If the sub-arrays 110- m in the hybrid array 100 are uniformly spaced in a linear configuration (e.g. 200), the weights will converge to the following form:

$$w_m(n) = \exp(jkmd_x^{(s)} \sin \theta) + v_m(n) \quad (4)$$

where k is the wavenumber of the RF carrier signal, θ is the “zenith” angle of arrival as illustrated in Fig. 2a, and $\mathbf{v}(n)$ is a noise vector.

If the sub-arrays 110- m in the hybrid array 100 are uniformly spaced in a planar configuration (e.g. 230), the weights will converge to the following form:

$$w_m(n) = \exp(jk(m_x d_x^{(s)} \sin \theta \cos \phi + m_y d_y^{(s)} \sin \theta \sin \phi)) + v_m(n) \quad (5)$$

where ϕ is the “azimuth” angle of arrival as illustrated in Fig. 2b. Note that for a planar array, the “zenith” angle of arrival θ is measured from the normal to the plane of the array.

Once the digital beamformer 165 converges, the angle of arrival estimation sub-module 155 analyses the weights $\mathbf{w}(n)$ according to the model in equation (4) or equation (5) to form an estimate $(\hat{\theta}, \hat{\phi})$ of the angle of arrival, given values for k , $d_x^{(s)}$ and $d_y^{(s)}$.

Search strategies

5 If the angle of arrival is not initially known, the phase shifters 130 cannot be set to the correct values to give each sub-array 110- m anything like its maximum gain. The digital beamformer 165 may therefore be unable to form a reasonable beam, and thus the angle of arrival cannot be estimated by the sub-module 155 by the method described above.

10 To form a coarse estimate of the angle of arrival, and thereby initialise the hybrid array 100, the digital processing module 150 takes one of several approaches (known as the “search strategy”). One search strategy is to divide the whole hybrid array 100 into multiple groups. The sub-array phase control sub-module 170 sets the phase shifters 130 in the analogue sub-arrays 110- m using equation (19) or (20) below, such that each group
15 monitors a different “look angle” spanning the field of view. The digital processing module 150 operates on the outputs from each separate group in sequence, keeping the phase shifters 130 fixed. The “look angle” monitored by the group that results in the highest-power output signal $z(n)$ is a coarse estimate of the angle of arrival. The reduced digital beamforming gain caused by the use of fewer than M sub-arrays at a time can be
20 compensated for by a longer convergence time in the beamforming module 165.

Another search strategy is for the digital processing module 150 to perform a coarse digital beamforming using only one element 120 in each analogue beamforming sub-array 110- m , making the phase of each element irrelevant. An equivalent approach is to set the initial phases of each analogue sub-array such that the beam pattern of the sub-

array has low directivity (i.e. is close to omni-directional). A coarse estimate of the angle of arrival may be then obtained using the method described above.

A third search strategy is for the sub-array phase control sub-module 170 to set all the phase shifters 130 in all the sub-arrays 110-*m* so as to monitor a particular “look angle” using equation (19) or (20) below. The digital processing module 150 then estimates the angle of arrival using either of the methods described herein, and also records the corresponding output signal power. This process is repeated while the “look angle” is stepped through multiple look angles that cover the field of view. At the end of the search, the coarse estimate of the angle of arrival is the angle estimate corresponding to the highest output signal power.

All the search strategies are executed by the sub-array phase control sub-module 170 in collaboration with the beamforming module 165.

Estimating the angle of arrival by Correlation

An alternative method of estimating the angle of arrival is for the estimation sub-module 155 to cross-correlate the signals $x_m(n)$ from adjacent digital branches 145 along the x-axis and the y-axis:

$$R_x = E \{ x_{m_y M_x + m_x}^*(n) x_{m_y M_x + m_x + 1}(n) \} \quad (6)$$

$$R_y = E \{ x_{m_y M_x + m_x}^*(n) x_{(m_y + 1) M_x + m_x}(n) \} \quad (7)$$

Defining

$$u_x = \frac{2\pi}{\lambda_c} d_x^{(s)} \sin \theta \cos \phi \quad (8)$$

$$u_y = \frac{2\pi}{\lambda_c} d_y^{(s)} \sin \theta \sin \phi \quad (9)$$

where λ_c is the wavelength of the RF carrier signal, then provided $d_x^{(s)}$ and $d_y^{(s)}$ are less than or equal to $\lambda_c / 2$, u_x and u_y will be in the range $(-\pi, \pi)$ and are equal to $\arg\{R_x\}$ and $\arg\{R_y\}$ respectively without any ambiguity. The angle of arrival could then be estimated directly from u_x and u_y , given values for λ_c , $d_x^{(s)}$ and $d_y^{(s)}$.

5 However, for a uniformly spaced planar configuration, $d_x^{(s)}$ and $d_y^{(s)}$ are typically greater than $\lambda_c / 2$, so u_x and u_y can be outside the range $(-\pi, \pi)$ and phase ambiguity will be present in R_x and R_y .

To handle this ambiguity, the estimation sub-module 155 carries out the method 300 illustrated in the flow chart in Fig. 3 to estimate the angle of arrival. In step 310, the
10 estimation sub-module 155 initialises two indices p and q for a double loop over the following ranges:

$$p = -\left\lfloor \frac{N_x}{2} \right\rfloor, -\left\lfloor \frac{N_x}{2} \right\rfloor + 1, \dots, 0, 1, \dots, \left\lfloor \frac{N_x}{2} \right\rfloor$$

$$q = -\left\lfloor \frac{N_y}{2} \right\rfloor, -\left\lfloor \frac{N_y}{2} \right\rfloor + 1, \dots, 0, 1, \dots, \left\lfloor \frac{N_y}{2} \right\rfloor$$

In step 320, the estimation sub-module 155 estimates the cross-correlations
15 iteratively over time n using all available sub-array outputs (to maximise the signal-to-noise ratio) as follows:

$$R_x^{(n)} = (1 - \mu)R_x^{(n-1)} + \mu \sum_{m_y=0}^{M_y-1} \sum_{m_x=0}^{M_x-2} x_{m_y M_x + m_x}^*(n) x_{m_y M_x + m_x + 1}(n) \quad (10)$$

$$R_y^{(n)} = (1 - \mu)R_y^{(n-1)} + \mu \sum_{m_x=0}^{M_x-1} \sum_{m_y=0}^{M_y-2} x_{m_y M_x + m_x}^*(n) x_{(m_y+1)M_x + m_x}(n) \quad (11)$$

where $0 < \mu < 1$ is an updating coefficient (typically set to 0.001).

The estimation sub-module 155 then at step 330 computes u_x and u_y values from $\arg\{R_x\}$ and $\arg\{R_y\}$ at the current p and q respectively, as follows:

$$u_x(p) = 2\pi p + \arg\{R_x\}, \quad (12)$$

$$u_y(q) = 2\pi q + \arg\{R_y\}, \quad (13)$$

5 where $[\cdot]$ denotes the operation of taking the integer part of a value.

Each pair $(u_x(p), u_y(q))$ represents a candidate beam. The phase control sub-module 170 at step 340 sets the phase shifts of the phase shifters 130 within each sub-array for the current (p, q) pair to

$$\alpha_i(p, q) = -\frac{X_i u_x(p)}{d_x^{(s)}} - \frac{Y_i u_y(q)}{d_y^{(s)}} \quad (14)$$

10 The beamforming sub-module 165 then at step 350 forms the beam as described above to produce the output signal $z_{p,q}(n)$, after which (at step 360) the estimation sub-module 155 computes and records the output signal power for the current (p, q) pair iteratively as

$$P^{(n)}(p, q) = (1 - \beta)P^{(n-1)}(p, q) + \beta |z_{p,q}(n)|^2 \quad (15)$$

15 where $0 < \beta < 1$ is an updating coefficient (typically set to 0.25).

The estimation sub-module 155 then at step 370 determines whether the double loop over p and q is complete; if not, p and q are updated at step 375 and the method 300 returns to step 320.

If the double loop is complete, the estimation sub-module 155 at step 380
20 determines the (p, q) pair that yielded the largest output signal power computed at step 360:

$$(p_{\max}, q_{\max}) = \arg \max_{p, q} P^{(n)}(p, q) \quad (16)$$

Finally, at step 390 the estimation sub-module 155 uses the maximising pair ($p_{\max}$, $q_{\max}$) to estimate the angle of arrival:

$$\hat{\theta} = \text{sgn}(u_x(p_{\max})) \sin^{-1} \left(\frac{\lambda_c}{2\pi} \sqrt{\frac{u_x(p_{\max})^2}{(d_x^{(s)})^2} + \frac{u_y(q_{\max})^2}{(d_y^{(s)})^2}} \right) \quad (17)$$

$$\hat{\phi} = \tan^{-1} \left(\frac{u_y(p_{\max})}{u_x(q_{\max})} \cdot \frac{d_x^{(s)}}{d_y^{(s)}} \right) \quad (18)$$

5 Due to the delay from the time when the phase shifts are loaded into the phase shifters 130 in sub-arrays 110- m to the time when a change of the beamformed output signal is observed, several (typically 4) iterations per (p , q) pair are preferable for step 360. If the number of iterations for each (p , q) pair is chosen so that the output power $P^{(n)}(p, q)$ of the corresponding beam can be calculated with sufficient accuracy, one pass
10 through the complete double loop will be sufficient to determine the most likely beam and hence estimate the angle of arrival. If fewer than that number of iterations are used, the double loop is repeated until the power of each beam calculated across multiple double loops is obtained with sufficient accuracy.

Setting the phase of the analogue branches

15 The sub-array phase control sub-module 170 uses the estimated angle of arrival $(\hat{\theta}, \hat{\phi})$ from the estimation sub-module 155 to set the phase of each phase shifter 130 in each analogue branch 115 via the control signals 175 as follows:

$$\alpha_i = -k(X_i \sin \hat{\theta} \cos \hat{\phi} + Y_i \sin \hat{\theta} \sin \hat{\phi}) \quad (19)$$

for the planar array, or

$$\alpha_i = -kX_i \sin \hat{\theta} \quad (20)$$

for the linear array.

In tracking mode, the sub-array phase control sub-module 170 periodically obtains an estimate of $u_x(p_{\max})$ and $u_y(q_{\max})$ from the estimation module 155 (which uses steps 320 and 330 of the method 300 with (p, q) set to $(p_{\max}, q_{\max})$), and updates the phase of each phase shifter 130 using equation (14), as in step 340 of the method 300.

5

Calibrating the array

Equations (4) and (5) hold if the sub-arrays 110- m are uniformly spaced and the signal chains 140- m are identical. In practice, there will be small deviations from uniform spacing, and imperfections due to component un-uniformity, temperature change, and component ageing in the signal chains 140- m , which cause the weight vector to converge to values whose phase deviates slightly from the models in Equations (4) and (5). If these deviations are not corrected by calibration, the estimation of angle of arrival may be affected and the performance of the hybrid array 100 may be sub-optimal.

If the sub-arrays 110- m are uniformly spaced, the phases between the signals output from any two adjacent digital branches 145 should have the same difference regardless of the phase deviation. This fact can be used to calibrate the digital branches. The calibration sub-module 160 analyses the signals $x_m(n)$ from each digital branch 145 to determine the phase deviation of each digital branch 145. To do this, the calibration sub-module 160 uses the method 300 to obtain an estimate of the “expected” phase difference, defined by equations (8) and (9), between any two adjacent digital branches 145. This estimate is then used to determine the phase deviation in each digital branch 145 as the difference between the expected phase difference and the actual phase difference between that digital branch 145 and an adjacent, previously calibrated digital branch. The calibration proceeds by induction in each direction from a designated reference digital

15
20

branch. The phase deviation is used by the beamforming sub-module 165 to correct the signals $x_i(n)$ before forming the beam.

The calibration sub-module 160 also calibrates each analogue branch 115. According to one embodiment, the sub-array phase control sub-module 170 optimises the
5 phase shifts applied by the phase shifters 130 in a sub-array 110- m in order to obtain the maximum-power output signal $x_m(n)$ from the corresponding digital branch 145. Since the angle of arrival is known from the angle of arrival estimation sub-module 155, the expected phase shift values, accurate to the last bit of the phase shifters, can be calculated from equations (19) and (20). The difference between the expected phase shift values and
10 the optimised phase shift values gives the phase deviation for each analogue signal branch. The deviation is applied by the phase control sub-module 170 to adjust the phase shifts of the phase shifters 130 in the sub-array. Calibration of analogue signal branches is preferably performed a few times a day.

The arrangements described are applicable to the data communication and sensing
15 industries, and particularly to satellite communication and other high data rate communication (mobile, point-to-point, and point-to-multipoint topologies). The disclosed arrangements are most beneficial for millimetre-wave to terahertz adaptive antenna arrays where tight element spacing makes it very difficult or impossible to do conventional digital or analogue beamforming alone. The typical operating range is 10 to 100 GHz, but the
20 arrangements are useful for frequencies as low as 400 MHz.

The foregoing describes only some embodiments of the present invention, and modifications and/or changes can be made thereto without departing from the scope and spirit of the invention, the embodiments being illustrative and not restrictive.

Claims:

1. A hybrid antenna array comprising:
 - (a) a plurality of digital branches, each digital branch including:
 - (i) an analogue beamforming sub-array, each sub-array having a plurality of
5 antenna elements, a phase shifter adapted to apply a phase shift to the signal from
each antenna element, and a combiner adapted to combine the phase shifted signals;
 - (ii) a signal chain adapted to convert the output of the sub-array to baseband;
and
 - (b) a digital processing module, including:
 - (i) an angle of arrival estimation sub-module adapted to estimate an angle of
10 arrival of a signal at the antenna elements;
 - (ii) a phase control sub-module adapted to control the phase shift applied by
each phase shifter depending on the estimated angle of arrival; and
 - (iii) a digital beamformer adapted to combine the baseband signals from the
15 digital branches using a weight vector to form an output signal.
2. The array according to claim 1, wherein the digital beamformer is adapted to
compute the weight vector from the baseband signals.
- 20 3. The array according to claim 1, wherein the digital beamformer is adapted to
compute the weight vector from the normalised baseband signals.
4. The array according to either of claim 2 or claim 3, wherein the digital beamformer
is further adapted to compute the weight vector from a reference signal.

5. The array according to claim 1, wherein the digital processing module is adapted to estimate the angle of arrival by:

- (a) cross-correlating the baseband signals from adjacent digital branches;
 - (b) for a plurality of candidate beams,
 - 5 (i) setting the phase shifts using the arguments of the cross-correlation values; and
 - (ii) computing the power of the output signal of the digital beamformer;
 - (c) determining the candidate beam giving the maximum output power; and
 - (d) estimating the angle of arrival from the cross-correlation values of the
- 10 determined candidate beam.

6. The array according to claim 1, wherein the digital processing module further comprises a calibration sub-module adapted to calibrate the digital beamformer by:

- (a) estimating the expected phase difference between the baseband signals from
- 15 adjacent digital branches;
- (b) determining the phase deviation of each digital branch as the difference between the expected phase difference and an actual phase difference between the baseband signals from the digital branch and an adjacent previously calibrated digital branch; and
- 20 (c) applying the determined phase deviation to the baseband signal from the corresponding digital branch.

7. The array according to claim 1, wherein the digital processing module further comprises a calibration sub-module adapted to calibrate each analogue beamforming sub-

25 array by:

- 20 -

(a) optimising the phase shifts applied by the phase shifters in the sub-array so as to obtain a maximum-power signal from the sub-array;

(b) determining the phase deviation for each analogue branch in the sub-array as the difference between the phase shift provided by the phase control sub-module and the
5 optimised phase shift for the analogue branch; and

(c) applying each phase deviation to adjust the phase shift applied by the corresponding phase shifter.

8. The array according to claim 1, wherein the sub-arrays are in a planar configuration.
10

9. The array according to claim 8, wherein each sub-array is a rectangular sub-array.

10. The array according to claim 8 or claim 9, wherein the array is uniformly spaced.

15 11. A method of estimating the angle of arrival of a signal at an antenna array comprising a plurality of digital branches and a digital beamformer, the method comprising:

(a) cross-correlating the baseband signals from adjacent digital branches;

(b) for a plurality of candidate beams,

20 (i) setting the phase shifts using the arguments of the cross-correlation values; and

(ii) computing the power of the output signal of the digital beamformer;

(c) determining the candidate beam giving the maximum output power; and

(d) estimating the angle of arrival from the cross-correlation values of the
25 determined candidate beam.

12. A method of calibrating an antenna array comprising a plurality of digital branches and a digital beamformer, the method comprising:

(a) estimating the expected phase difference between the baseband signals from
5 adjacent digital branches;

(b) determining the phase deviation of each digital branch as the difference between the expected phase difference and an actual phase difference between the baseband signals from a digital branch and an adjacent previously calibrated digital branch; and

10 (c) applying each phase deviation to the baseband signal from the corresponding digital branch.

13. A method of calibrating an antenna array comprising a plurality of analogue branches, each analogue branch comprising an antenna element and a phase shifter, the
15 method comprising:

(a) optimising the phase shifts applied by the phase shifters to an input signal to the array so as to obtain a maximum-power output signal from the array;

(b) determining expected values of the phase shifts using an angle of arrival of the input signal;

20 (c) determining the phase deviation for each analogue branch in the array as the difference between the expected phase shift and the optimised phase shift for the analogue branch; and

(d) applying each phase deviation to adjust the phase shift applied by the corresponding phase shifter.

- 1 / 3 -

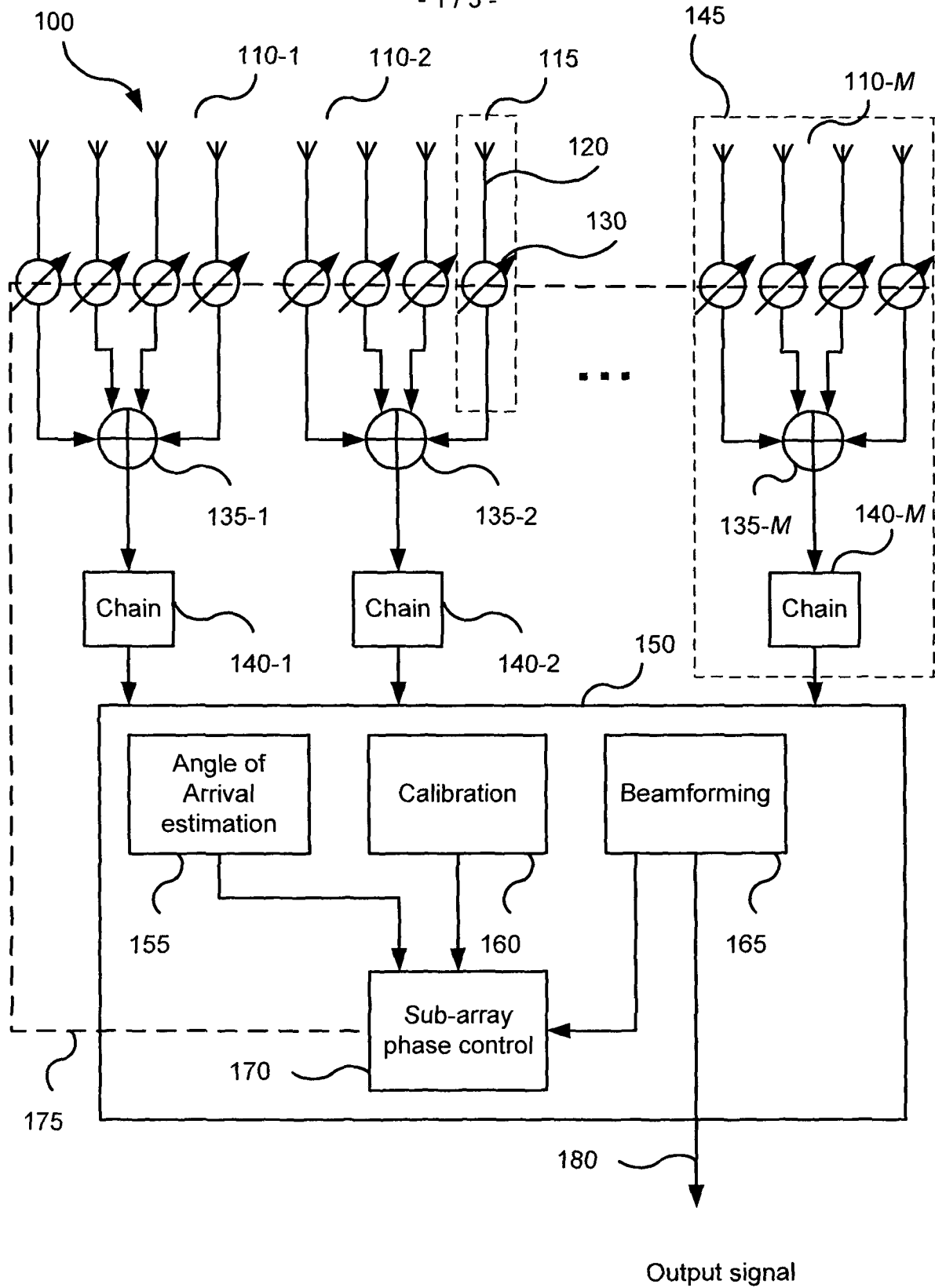
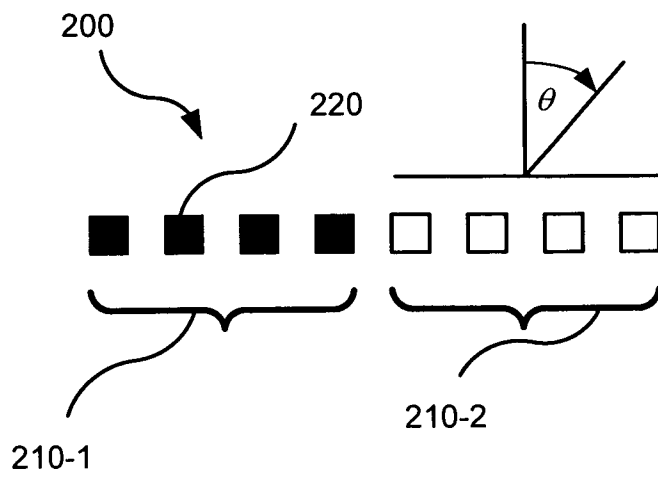
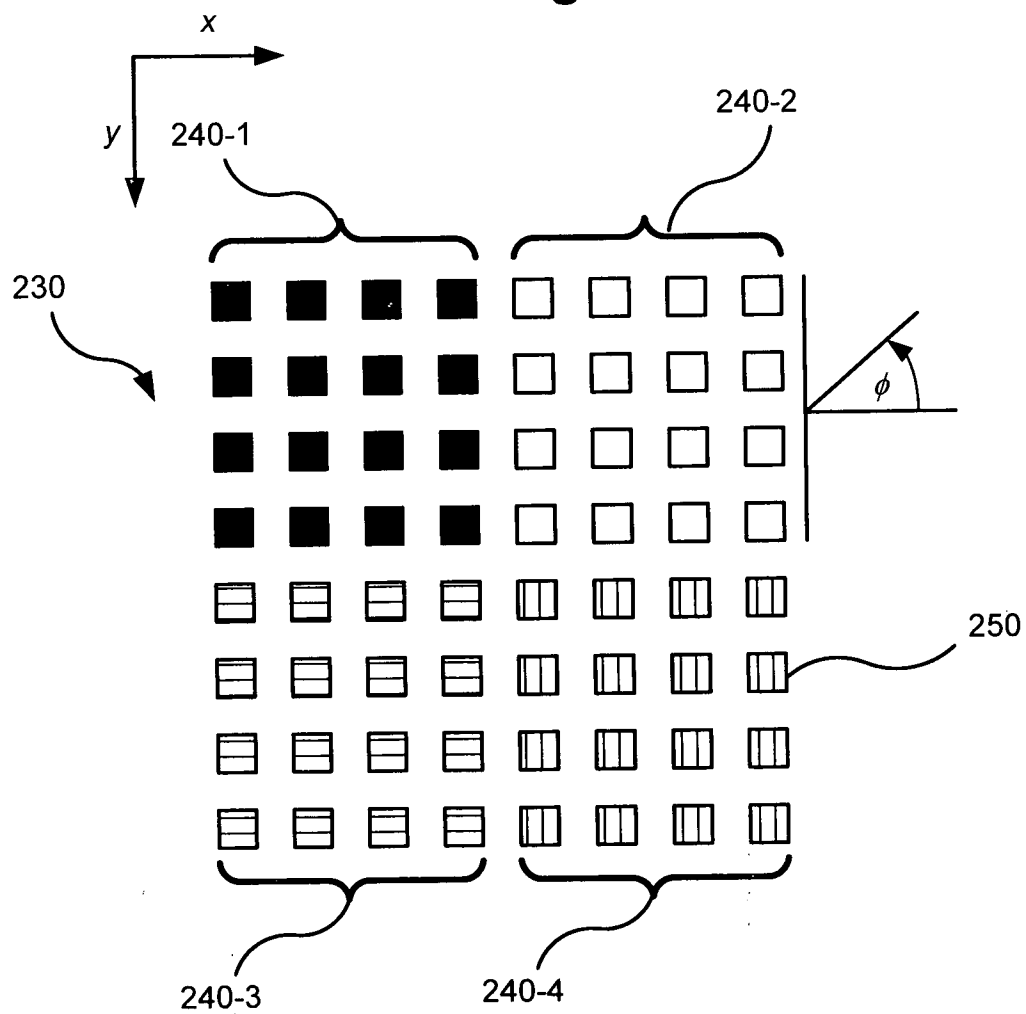
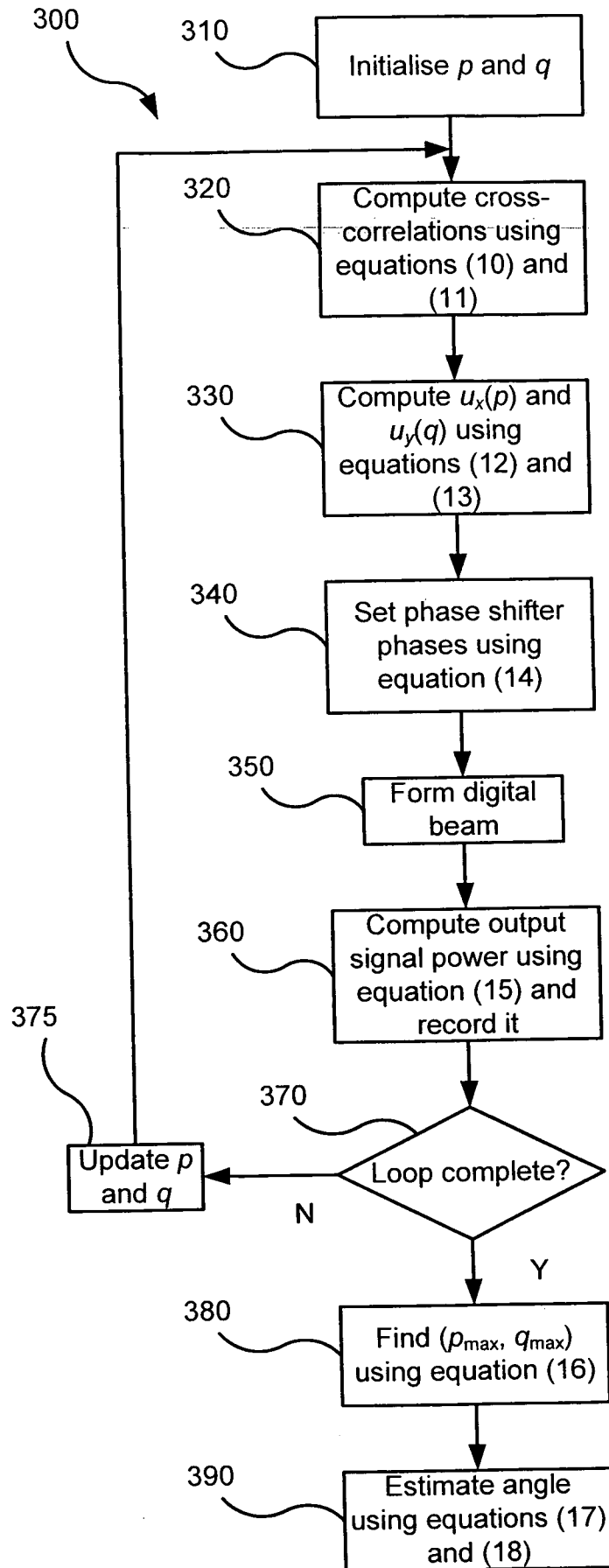


Fig. 1

- 2 / 3 -

**Fig. 2a****Fig. 2b**

- 3 / 3 -

**Fig. 3**

INTERNATIONAL SEARCH REPORT

International application No.

PCT/AU2010/000091

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

H01Q 3/36 (2006.01)

G01S 3/42 (2006.01)

H01Q 3/26 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPOQUE : IPC AS ABOVE & KEYWORDS HYBRID ANTENNA ARRAY, BEAMFORMING, PHASE SHIFT, ANALOG, DIGITAL & SIMILAR WORDS

INTERNET & KEYWORDS AS ABOVE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2007/095354 A2 (SIBeam) 23 August 2007 Abstract; Fig. 3; Paras [0060] – [0067], [0070] - [0077]	
A	US 2003/0016173 A1 (Obayashi) 23 January 2003 Abstract; Fig. 6; Paras [0058] – [0062]	
A	US 6404803 B1 (Wang et al.) 11 June 2002 Abstract; Fig. 1; Col. 4, Lines 5 to 57 & Claims	
A	US 6483459 B1 (Hou et al.) 19 November 2002 Abstract ; Fig. 1 ; Col. 4, Lines 16 to 25 & Claims	

☒ Further documents are listed in the continuation of Box C

☒ See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"E" earlier application or patent but published on or after the international filing date

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"O" document referring to an oral disclosure, use, exhibition or other means

"&" document member of the same patent family

"P" document published prior to the international filing date but later than the priority date claimed

Date of the actual completion of the international search
22 March 2010

Date of mailing of the international search report
29 MAR 2010

Name and mailing address of the ISA/AU
AUSTRALIAN PATENT OFFICE
PO BOX 200, WODEN ACT 2606, AUSTRALIA
E-mail address: pct@ipaustralia.gov.au
Facsimile No. +61 2 6283 7999

Authorized officer
AMOD PRADHAN
AUSTRALIAN PATENT OFFICE
(ISO 9001 Quality Certified Service)
Telephone No. : +61 2 6283 2510

INTERNATIONAL SEARCH REPORT

International application No.

PCT/AU2010/000091

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	Jeon et al., "A Novel Planar Array Smart Antenna System With Hybrid Analog-Digital Beamforming", (2001) IEEE Abstract; Fig. 1; 'II. Hybrid Analog-Digital Beamformer' On Page 2, Left Column	
A	Rezk et al., "Performance Comparison Of A Novel Hybrid Smart Antenna System Versus The Fully Adaptive And Switched Beam Antenna Arrays", (2005) IEEE Abstract; 'IV. Conclusions'	
A	Zhang et al., "Hybrid Smart Antenna System Using Directional Elements - Performance Analysis In Flat Rayleigh Fading", IEEE Transactions On Antennas And Propagation, Vol. 51, No. 10, October 2003 Abstract; 'I. Introduction'; Figs. 1, 3, 5, 6; Page 2927, Right Column, 3rd Paragraph; Page 2931, Right Columns, Last Paragraph; 'V. Conclusions'	
A	Budsabathon et al., "Optimum Beamforming For Pre-FFT OFDM Adaptive Antenna Array", IEEE Transactions On Vehicular Technology, Vol. 53, No. 4, July 2004 Abstract; Figs. 1, 5, 7; Page 952, Left Column, 1st paragraph	

INTERNATIONAL SEARCH REPORT

International application No.

PCT/AU2010/000091

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

SEE EXTRA SHEET

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.: **1 TO 10**

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/AU2010/000091

Supplemental Box I

(To be used when the space in any of Boxes I to IV is not sufficient)

Continuation of Box No: III

This International Application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept.

In assessing whether there is more than one invention claimed, I have given consideration to those features which can be considered to potentially distinguish the claimed combination of features from the prior art. Where different claims have different distinguishing features they define different inventions.

This International Searching Authority has found that there are different inventions as follows:

GROUP 1: CLAIMS 1 TO 10 (INDEPENDENT CLAIM 1)

A hybrid antenna array comprising (a) a plurality of digital branches, each branch including (i) an analogue beamforming sub-array, each sub array having a plurality of antenna elements, a phase shifter adapted to apply a phase shift to the signal from each antenna element, and a combiner adapted to combine the phase shifted signals; (ii) a signal chain adapted to convert the output of the sub-array to baseband; and (b) a digital processing module, including: (i) an angle of arrival estimation sub-module adapted to estimate an angle of arrival of a signal at the antenna elements; (ii) a phase control sub-module adapted to control the phase shift applied by each phase shifter depending on the estimated angle of arrival; and (iii) a digital beamformer adapted to combine the baseband signals from the digital branches using a weight vector to form an output signal. It is considered that 'a digital beamformer adapted to combine the baseband signals from the digital branches using a weight vector to form an output signal' constitutes a **FIRST** special technical feature.

GROUP 2: INDEPENDENT CLAIM 11

A method of estimating the angle of arrival of a signal at an antenna array comprising a plurality of digital branches and a digital beamformer, the method comprising: (a) cross-correlating the baseband signals from adjacent digital branches; (b) for a plurality of candidate beams, (i) setting the phase shifts using the arguments of the cross-correlation values; and (ii) computing the power of the output signal of the digital beamformer; (c) determine the candidate beam giving the maximum power output; and (d) estimating the angle of arrival from the cross-correlation values of the determined candidate beam. It is considered that 'estimating the angle of arrival from the cross-correlation values of the determined candidate beam' constitutes a **SECOND** special technical feature.

GROUP 3: INDEPENDENT CLAIM 12

A method of calibrating an antenna array comprising a plurality of digital branches and digital beamformer, the method comprising: (a) estimating the expected phase difference between the baseband signals from adjacent digital branches; (b) determining the phase deviation of each digital branch as the difference between the expected phase difference and an actual phase difference between the baseband signals from a digital branch and an adjacent previously calibrated digital branch and (c) applying each phase deviation to the baseband signal from the corresponding digital branch. It is considered that 'applying each phase deviation to the baseband signal from the corresponding digital branch' constitutes a **THIRD** special technical feature.

GROUP 4: INDEPENDENT CLAIM 13

A method of calibrating an antenna array comprising a plurality of analogue branches, each analogue branch comprising an antenna element and a phase shifter, the method comprising: (a) optimising the phase shifts applied by the phase shifters to an input signal to the array so as to obtain a maximum power output signal from the array; (b) determining expected values of the phase shifts using an angle of arrival input signal; (c) determining the phase deviation for each analogue branch in the array as the difference between the expected phase shift and the optimised phase shift for the analogue branch; and (d) applying each phase deviation to adjust the phase shift applied by the corresponding phase shifter. It is considered that 'applying each phase deviation to adjust the phase shift applied by the corresponding phase shifter' constitutes a **FOURTH** special technical feature.

PCT Rule 13.2, first sentence, states that unity of invention is only fulfilled when there is a technical relationship among the claimed inventions involving one or more of the same or corresponding special technical features. PCT Rule 13.2, second sentence, defines a special technical feature as a feature which makes a contribution over the prior art.

Continued in Supplemental Box II

INTERNATIONAL SEARCH REPORT

International application No.

PCT/AU2010/000091

Supplemental Box II

(To be used when the space in any of Boxes I to VIII is not sufficient)

Continuation of Box No: III

Each of the abovementioned groups of claims has a different special technical feature and they do not share any feature which could satisfy the requirement for being a special technical feature. Because there is no common special technical feature it follows that there is no technical relationship between the identified inventions. Therefore the claims do not satisfy the requirement of unity of invention *a priori*.

NOTE:

While it may appear that the independent claims share a common feature of an antenna array, it is noted that an independent claim 1 defines a hybrid antenna array with an analogue and a digital beamformer, independent claims 11 and 12 define the estimation of an angle of arrival and calibration of an antenna array comprising a digital beamformer respectively and independent claim 13 defines calibration of an antenna array comprising an analogue beamformer.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/AU2010/000091

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
WO	2007/095354	AU	2007215029	CN	101416416	EP	1992083
		KR	20080104311	US	2007/205943		
US	2003/0016173	JP	2002076749	US	6466165	US	6650292
		US	6750817	US	2002/057219	US	2003/006934
US	6404803	AU	11224/02	EP	1336263	WO	2002035745
US	6483459	NONE					
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.							
END OF ANNEX							