

WIRELESS SIGNAL PROCESSING METHODS AND APPARATUSES
INCLUDING DIRECTIONS OF ARRIVAL ESTIMATION

Technical Field

5 The present invention is related to the field of communication in general, and wireless communication, in particular.

BACKGROUND

Advances in integrated circuit, microprocessor, networking, telecommunication and other related technologies have led to wide spread
10 adoption of wireless communication, e.g. mobile wireless "cell" phones. In the case of wireless communication, such as mobile wireless "cell" phones, typically, a mobile wireless "cell" phone (also referred to as a mobile handset), communicates with a "nearby" service station (also referred to as a base station), which relays the communication signals for the mobile handset. The service/base
15 station provides the relay service for all mobile handset in its coverage area (its "cell"). Thus, a service/base station typically receives and processes communication signals from a number of mobile handsets in its "cell" concurrently.

Use of multiple antennas at the service/base station for receiving the communication signals from the mobile handsets have become popular, as it has
20 several advantages in terms of enhancing the capacity and throughput of the wireless communication system. Various signal processing techniques are employed to process the received communication signals, including but not limited to "space-time" processing techniques.

Among the space-time processing techniques, beamforming is one of the
25 promising areas of interest for enhancing the strength of signals received from a desired direction. One known technique is the employment of a known training sequence to estimate the optimum weights (e.g. using least mean square (LMS)),

for beamforming to a desirable direction. Other known techniques for estimating the directions of arrival (DOAs) include employment of the Bartlett processor or the MUSIC (*Multiple Signal Classification*) technique.

5 Training has the disadvantage of incurring overhead in the throughput of the system, and convergence may take longer time than the time available to make the determination. The latter techniques require a large number of snapshots of the received signals to provide a good estimate of a correlation matrix reflective of the correlation (or the lack thereof) of the received signals from the independent signal sources.

10 Additionally, while each communication signal typically has a number of multipaths, due to environmental factors, such as reflection off structures and so forth, these techniques typically estimate the DOA based only on the most dominant multipath of a signal.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention will be described by way of the accompanying drawings in which like references denote similar elements, and in
5 which:

Figure 1 illustrates a communication environment suitable for practicing the present invention, in accordance with one embodiment;

Figure 2 illustrates a portion of the operational flow for determining the directions of arrival of J signals wirelessly transmitted from J signal sources, in
10 accordance with one embodiment;

Figure 3 illustrates a portion of the operational flow for determining the directions of arrival of L multipaths of J signals wirelessly transmitted from J signal sources, in accordance with one embodiment;

Figure 4 illustrates a computer system suitable for use to practice one or
15 more aspects of one or more of the signal processing methods of **Fig. 2-3**, in accordance with one embodiment.

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DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

Embodiments of the present invention include but are not limited to methods and apparatuses for determining the direction of arrivals of a number of
25 signals wirelessly transmitted. Embodiments of the present invention also include methods and apparatuses for determining the direction of arrivals of multipaths of a number of signals wirelessly transmitted.

In the following description, various aspects of embodiments of the present invention will be described. However, it will be apparent to those skilled in the art that other embodiments may be practiced with only some or all of the described aspects. For purposes of explanation, specific numbers, materials and configurations are set forth in order to provide a thorough understanding of the embodiments. However, it will be apparent to one skilled in the art that other embodiments may be practiced without the specific details. In other instances, well-known features are omitted or simplified in order not to obscure the description.

Various operations will be described as multiple discrete operations in turn, in a manner that is most helpful in understanding the embodiments, however, the order of description should not be construed as to imply that these operations are necessarily order dependent. In particular, these operations need not be performed in the order of presentation.

The phrase "in one embodiment" is used repeatedly. The phrase generally does not refer to the same embodiment, however, it may. The terms "comprising", "having" and "including" are synonymous, unless the context dictates otherwise.

Referring now to **Fig. 1** wherein an overview of a communication environment suitable for practicing the present invention, in accordance with one embodiment, is shown. As illustrated, for the embodiment, communication environment **100** includes *J* mobile handsets **102a-102j** and base station **106**, communicatively coupled to each other. Base station **106** relays communication signals for mobile handsets **102a-102j** including receiving signals wirelessly transmitted by the handsets. The received signals, among other things, may be processed and forwarded to another signal processing node (not shown) of a wireless communication service network, to which base station **106** is coupled,

and/or to a signal processing node (not shown) of a PSTN (Public Switched Telephone Network).

For the embodiment, base station **106** includes N antennas **108a-108n**, RF unit **110**, and signal processing unit **110**, coupled to each other as shown (RF =
5 Radio Frequency). Antennas **108a-108n** are employed to transmit to, and receive signals from mobile handsets **102a-102j**. Additionally, antennas **108a-108n** may be employed for other purposes. Antennas **108a-108n** may also be referred to as sensors. For the purpose of this application, the two terms are synonymous.

RF unit **110** is employed to down convert RF signals received by antennas
10 **108a-108n** into baseband signals, or up convert baseband signals into RF signals for transmission by antennas **108a-108n**.

Signal processing unit **110** is employed to process the down converted baseband signals, and process outbound signals for up conversion. For the embodiment, signal processing unit **110**, includes in particular DOA Estimation
15 unit **112** and Beamforming unit **114**, coupled to each other and to RF unit **110** as shown.

In various embodiments, DOA Estimation unit **112** estimates the DOAs of the J signals (J being an integer), to be described more fully below referencing **Fig. 2**. For these embodiments, Beamforming unit **114** forms the corresponding
20 weighted output signals based at least in part on the DOAs of the J signals estimated by DOA Estimation unit **112**.

In other embodiments, DOA Estimation unit **112** estimates the DOAs of the L multipaths (L being an integer) of the J signals, to be described more fully referencing **Fig. 3**. Some embodiments support one of the two methods to be
25 described referencing **Fig. 2** and **3**. Other embodiments support both. For those embodiments supporting both methods illustrated by **Fig. 2-3**, the embodiments

may also support configuration of one of the two methods as the current operating method. The configuration may be supported in a static or dynamic approach.

For the latter embodiments, Beamforming unit **114** forms the corresponding output signals based at least in part on the DOAs of the L multipaths of the J signals estimated by DOA Estimation unit **112**. More specifically, Beamforming unit **114** determines a number of corresponding weights and forms the corresponding output signals based at least in part on weighted contributions of the L multipaths of the J signals estimated by DOA Estimation unit **112**.

Except for the advantageous manners base station **106** acquires signals **104a-104j**, mobile handsets **102a-102j** and RF units **110** represent a broad range of these elements. A computer system suitable for hosting a software implementation of DOA Estimation unit **112** and Beamforming unit **114** will be further described below referencing **Fig. 4**. The software implementation may be developed employing any one or more of a number of programming languages. However, the present invention anticipates all or portions of DOA Estimation unit **112** and Beamforming unit **114** may be implemented in hardware, using e.g. one or more Application Specific Integrated Circuit (ASIC) or Field Programmable Logic Devices. One of ordinary skill in the art would be able to do so, based on the description provided herein.

For the remaining descriptions to follow, and for the claims, the following conventions are employed:

- boldface-capital letters, such as **A**, **M**, represent matrices or subspaces,

- boldface-small letters, such as **v**, represent vectors, and

- non-boldface letters, such as "s", represent scalars.

Referring now to **Fig. 2**, a flow diagram illustrating the operation flow of DOA Estimation unit **112** for determining the DOAs of the J signals in accordance with one embodiment, is shown. The embodiment assumes the followings:

The J independent signals impinge on the N antenna array in J distinct directions $\theta_1, \dots, \theta_J$, where the angles θ_j are measured with respect to the endfire direction.

The output signal vector for a single snapshot of the received signal is given by

$$(1) \quad \mathbf{x}(t) = \mathbf{A}\mathbf{s}(t) + \mathbf{n}(t)$$

10 where $\mathbf{x}(t)$ is the $N \times 1$ column vector written as,

$$(2) \quad \mathbf{x}(t) = [x_1(t), \dots, x_L(t)]^T$$

$$(3) \quad \mathbf{A} = [\mathbf{a}(\theta_1), \dots, \mathbf{a}(\theta_J)], \text{ where } \mathbf{A} \text{ is the } N \times J \text{ directional response}$$

matrix

$$(4) \quad \mathbf{a}(\theta_j) = \begin{bmatrix} 1 & e^{-ikd \cos \theta_j} & \dots & e^{-i(L-1)kd \cos \theta_j} \end{bmatrix}^T, \quad j = 1, \dots, J$$

15 are the signal directional vectors. Each $\mathbf{a}(\theta_j)$ vector has the dimension $N \times 1$.

$$(5) \quad \mathbf{s}(t) = [s_1(t), \dots, s_J(t)]^T, \quad \mathbf{s}(t) \text{ is the } J \times 1 \text{ vector that contains the}$$

J signals transmitted by J independent sources.

20 $k = 2\pi f_0 / c$, f_0 being the center frequency, and c being speed of electromagnetic wave, k being the wavelength, and d is the spacing between antenna elements and t corresponds to the time index..

Thus, $\mathbf{x}(t)$ is the linear combination of J -linearly independent Vandermonde vectors, each corresponding to a source direction, and $\mathbf{x}(t)$ may be considered as

$$25 \quad (6) \quad \mathbf{x}(t) = \mathbf{a}(\theta_1)s_1(t) + \dots + \mathbf{a}(\theta_J)s_J(t)$$

In Equation (3), matrix $\mathbf{A}$ represents a basis that spans a J -dimensional subspace, to which $\mathbf{x}(t)$ belongs. Accordingly, $\mathbf{x}(t)$ in its decomposition has one of the directional vectors as its element.

Hence, there exists a correlation such that the intersection of the one-dimensional subspace spanned by $\mathbf{x}(t)$ (output signal vector for a single snapshot) and any of its J -signal directional vectors is non-zero.

Therefore, if θ_i does not correspond to one of true source directions i.e. $\theta_i \notin (\theta_1, \dots, \theta_J)$, the intersection between $\mathbf{x}(t)$ and $\mathbf{a}(\theta_i)$ will be zero.

Accordingly, the computational problem is formulated as

$$(7) \quad \mathbf{x}(t) \cap \mathbf{a}(\theta_i) = 0, \text{ for } \theta_i \notin (\theta_1, \dots, \theta_J)$$

$$(8) \quad \mathbf{x}(t) \cap \mathbf{a}(\theta_i) \neq 0 \text{ for } \theta_i \in (\theta_1, \dots, \theta_J)$$

The $N \times 2$ -matrix formulated as $\mathbf{D}(t) = [\mathbf{x}(t), \mathbf{a}(\theta_i)]$ will have rank deficiency or close to rank deficiency if $\theta_i \in (\theta_1, \dots, \theta_J)$.

Hence, in determining the DOA of the J signals $\theta_1, \dots, \theta_J$, the process of **Fig. 2** first selects a trial direction for a signal source j , $\sim \theta_i$, block **202**.

On selecting a trial direction, the process proceeds to compute

a first coefficient (9a) $r_{11} = \|\mathbf{x}(t)\|$, and

a first orthonormal vector (9b) $\mathbf{q}_1 = \frac{\mathbf{x}(t)}{r_{11}}$, block **204**.

On computing the first coefficient and the first orthonormal vector, the process proceeds to compute

a second coefficient (10a) $r_{12} = \mathbf{q}_1^H \mathbf{a}(\sim \theta_i)$,

a second orthonormal vector (10b) $\mathbf{q}_2 = \mathbf{a}(\sim \theta_i) - r_{12} \mathbf{q}_1$, and

a third coefficient (10c) $r_{22} = \|\mathbf{q}_2^H \mathbf{a}(\sim \theta_i)\|$, block **206**.

Then, the process proceeds to evaluating a function

$$(11) \quad B(\theta) = \frac{1}{r_{22}} \text{ for } \sim \theta_i, \text{ and}$$

determines whether the evaluation yields a peak value for the function. If so, the trial direction is considered to be one of the DOAs of the J signals.

At block **210**, the process determines whether additional directions are to be determined. If so, the process returns to block **202**, and continues from there as earlier described. If not, the process terminates.

Referring now to **Fig. 3**, a flow diagram illustrating the operation flow of DOA Estimation unit **112** for determining the DOA of L coherent multipaths of J signals in accordance with one embodiment, is shown. The embodiment includes an initial determination of the DOAs of the J signals, and the determined DOA of the J signals are then employed, along with other information, to determine the DOAs of the L multipaths of the J signals.

The signal corresponding to j th source and L coherent multipaths at the base station is given by

$$(12) \quad x_j(t) = \sum_{l=1}^L R_{jl} e^{i2\pi(f_d \cos\theta_{jl} - f\tau_{jl})} s(t - \tau_{jl})$$

Extending the above equation for N -element antenna array, the following relationship is obtained.

$$(13) \quad \mathbf{x}_j(t) = \sum_{l=1}^L \mathbf{v}(\theta_{jl}) R_{jl} e^{i2\pi(f_d \cos\theta_{jl} - f\tau_{jl})} s(t - \tau_{jl})$$

where $\mathbf{v}(\theta_{jl}) = [1 \quad e^{\frac{-i2\pi \cos\theta_{jl}}{\lambda}} \quad e^{\frac{i4\pi \cos\theta_{jl}}{\lambda}} \quad \dots \quad e^{\frac{i2\pi(N-1)\cos\theta_{jl}}{\lambda}}]^T$ is the array

response vector for jl -th multipath component. The notations in the above have the following meanings.

R_{jl} in the signal strength or amplitude of the l 'th multipath.

$f_d \cos\theta_{jl}$ is the Doppler shift of the jl 'th multipath ,

$\tau_{jl} = r_{jl}/c$ is the time delay of the of the jl -th multipath,

r_{jl} is the range of the jl -th multipath, and

c is the speed of electromagnetic wave,

θ_{jl} is DOA corresponding to jl -th multipath.

L is the number of dominant multipaths for j -th source.

Under the assumption that multipath delay spread

$$T = \max(\tau_{jl}) - \min(\tau_{jl}) \ll 1/B,$$

5 where B is the bandwidth of the signal,

$s_j(t)$, the base band signal of the j th source can be modeled as a narrowband signal, that is, $s(t - \tau_{jl}) \approx s(t - \tau_0)$, where $\tau_0 \in [\min(\tau_i), \max(\tau_i)]$.

$\mathbf{x}_j(t)$ is also written as

$$(14) \quad \mathbf{x}_j(t) = \sum_{l=1}^L \mathbf{v}(\theta_{jl}) R_{jl} e^{i\varphi_{jl}(t)} s(t - \tau_{jl})$$

10

where

$$(15) \quad \varphi_{jl} = 2\pi\pi(f_d \cos\theta_{jl} - f\tau_{jl})$$

Further, all multipaths from the mobile arrive at the base station array uniformly within $\pm \Delta$ around the mean angle of the arrival θ_j .

Further, assuming the signals are narrowband, the complex baseband

15 signal vector can be written as

$$(16) \quad \mathbf{x}_j(t) \approx s_j(t - \tau_0) \left(\sum_{l=1}^L \mathbf{v}(\theta_j) R_{jl} e^{i\varphi_{jl}(t)} \right)$$

Further letting

$$(17) \quad \mathbf{a}_j(t) = \sum_{l=1}^L \mathbf{v}(\theta_j) R_{jl} e^{i\varphi_{jl}(t)}$$

20

be an Array Response vector for L number of coherent multipaths corresponding to j 'th source.

Use of the conventional algorithms like MUSIC leads to the estimation of the same direction

θ_j , since all the L multipaths corresponding to that source are coherent.

Hence θ_{jl} may be replaced by θ_j .

25

In such a case the above equation can be approximated as

$$(18) \quad \mathbf{a}_j(t) \approx \mathbf{v}(\theta_j) \beta_j, \quad \text{where} \quad \beta_j = \sum_{l=1}^L R_{jl} e^{i\varphi_{jl}(t)}$$

For J -users the signal vector at the array is given by

$$(19) \quad \mathbf{x}(t) = \mathbf{x}_1(t) + \mathbf{x}_2(t) + \dots + \mathbf{x}_J(t) = \sum_{j=1}^J s_j(t) \mathbf{a}_j + \mathbf{n}(t)$$

$\mathbf{n}(t)$ is the noise vector (column), noise is assumed to be spatially and temporally white.

$$(20) \quad \mathbf{R} = E[\mathbf{y}(t)\mathbf{y}(t)^H] \\ = \mathbf{A}\Phi\mathbf{A}^H + \sigma^2\mathbf{I}$$

$\mathbf{R}$ is a correlation matrix. It is obtained from the outer-products of the received signal+noise vectors $\mathbf{x}(t)$ and averaged over several snapshots.

Averaging is denoted by E .

10 H denotes the 'Hermitian(transpose and conjugate).

$\mathbf{A}$ is the matrix of size $N \times J$ (N -antennas, J -sources);

σ^2 is the noise variance,

$\mathbf{I}$ is the $N \times N$ identity matrix and

$$(21) \quad \Phi = E[\mathbf{s}(t)\mathbf{s}(t)^H] \text{ is the } J \times J \text{ source covariance matrix.}$$

15 $\mathbf{s}(t)$ is baseband signal powers lying along the diagonal elements of Φ .

It's size is $J \times J$, where J is the number of sources. Noise covariance is given by

$$(22) \quad E[\mathbf{n}(t)\mathbf{n}^H(t)] = \sigma_n^2\mathbf{I}$$

20 So, letting the eigenvalues of $\mathbf{R}$, be arranged in descending order, and denoted by $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_N$, as well as letting $\mathbf{u}_1, \dots, \mathbf{u}_N$ be the corresponding eigenvectors, where the eigenvalues λ_n are given by

$$(23) \quad \lambda_n = \begin{cases} v_n + \sigma^2 & \text{for } n = 1, \dots, K \\ \sigma^2 & \text{for } n = K + 1, \dots, N \end{cases}$$

$\mathbf{U}_s = [\mathbf{u}_1, \dots, \mathbf{u}_J]$ may be considered as the signal subspace, and

$\mathbf{U}_n = [\mathbf{u}_{J+1}, \dots, \mathbf{u}_N]$ may be considered as the noise subspace.

25 $\mathbf{U}_n \mathbf{v}(\theta_j) = 0$ for $j = 1, \dots, J$, and elsewhere $\mathbf{U}_n \mathbf{v}(\theta_j) \neq 0$.

The embodiment assumes that the subspace spanned by the estimated eigenvectors $\mathbf{U}_s = [\mathbf{u}_1, \dots, \mathbf{u}_J]$ corresponds to the space spanned by the J -true source directions. It should be noted that j -th eigenvector corresponds to L -coherent multipaths due to the j -th source. Estimation of the j -th source direction θ_j can be done by any well known method like MUSIC. The embodiment searches within the direction range $\theta_j \pm \Delta$, centered on the determined DOA of the j -th source θ_j , to determine the L multipaths for j -th source.

Thus, signal vector $\mathbf{x}_j(t)$ can be considered as

$$\mathbf{x}_j(t) = [\mathbf{v}(\theta_{j1}) \quad \mathbf{v}(\theta_{j2}) \quad \dots \quad \mathbf{v}(\theta_{jL})] \tilde{\mathbf{s}}_{jl}$$

$$(24) \quad \text{where} \quad \tilde{\mathbf{s}}_{jl} = R_{jl} e^{i2\pi(f_d \cos \theta_{jl} - f\tau_{jl})} s_j(t - \tau_{jl})$$

$$(25) \quad \mathbf{x}_j(t) \in \text{span}\{\mathbf{v}(\theta_{j1}), \dots, \mathbf{v}(\theta_{jL})\}.$$

Thus, as illustrated in **Fig. 3**, the process for searching for the set $\Theta_j = (\theta_{j1}, \theta_{j2}, \dots, \theta_{jL})$ where $\theta_{jl} \in (\theta_j \pm \Delta), l = 1, 2, \dots, L$, starts with the process first selecting a trial direction set $\Theta = (\theta_{jk_1}, \theta_{jk_2}, \dots, \theta_{jk_L})$ for L multipaths of the j th source, block **302**.

The processing of finding $\Theta = \Theta_j$, that is,

$$(\theta_{jk_1}, \theta_{jk_2}, \dots, \theta_{jk_L}) = (\theta_{j1}, \theta_{j2}, \dots, \theta_{jL}) \text{ is explained as follows.}$$

First, the process selects randomly a set $(\theta_{jk_1}, \theta_{jk_2}, \dots, \theta_{jk_L})$

Second, the process forms the following matrix

$$\mathbf{D}(\theta) = [\mathbf{v}(\theta_{jk_1}) \quad \mathbf{v}(\theta_{jk_2}) \quad \dots \quad \mathbf{v}(\theta_{jk_L}) \quad \mathbf{u}_j] \quad \text{where} \quad \theta_{jk_l} \in (\theta_j \pm \Delta)$$

Third, the process computes the following relationships

$$(26) \quad r_{11} = \|\mathbf{v}(\theta_{jk_1})\|_2, \text{ and}$$

$$(27) \quad \mathbf{q}_1 = \frac{\mathbf{v}(\theta_{jk_1})}{r_{11}}, \text{ block } \mathbf{304}.$$

$\|\cdot\|_2$ is the 2-norm of the vector.

Similarly, for following coefficients and vectors, the process computes

$$(28) \quad r_{il} = \mathbf{q}_i^H \mathbf{v}(\theta_{jk_l}); \quad 1 \leq i \leq l-1; \quad l = 2, \dots, L+1$$

$$(29) \quad r_{ll} = \left\| \mathbf{v}(\theta_{jk_l}) - \sum_{i=1}^{l-1} r_{il} \mathbf{q}_i \right\|_2, \quad l = 2, \dots, L+1, \text{ and}$$

$$(30) \quad \mathbf{q}_l = [\mathbf{v}(\theta_{jk_l}) - \sum_{i=1}^{l-1} r_{il} \mathbf{q}_i] / r_{ll}, \quad l = 2, \dots, L+1, \text{ block } \mathbf{306}.$$

The computation is performed until $l=L+1$, that is obtaining $r_{L+1,L+1}$.

Then, at block **308**, the process computes the function

$$(31) \quad B(\Theta_j) = \frac{1}{r_{L+1,L+1}}.$$

If the result of $B(\Theta_j)$ yields a “new” set of peak values, the trial direction set Θ is set as the directions of arrival of the L strong multipaths.

At block **310**, a determination is made whether the process is to be repeated. The number of trials to repeat may be predetermined, for operating efficiency, or based on a predetermined threshold of diminishing marginal improvements.

If another trial set is to be evaluated, the process returns to block **302**.

Eventually, the criteria to terminate estimation process is met, and the process terminates. The then current estimates of the L multipath directions $\hat{\Theta}_j = \{\hat{\theta}_{j1}, \dots, \hat{\theta}_{jL}\}$ are used to obtain the combined signal $z(t)$ (See Figure.1) as

$$(32) \quad z(t) = \sum_{l=1}^L \sum_{n=1}^N x_n w_{nl} \quad \text{where} \quad w_{nl} = e^{-ikd(n-1)\cos\hat{\theta}_{jl}}$$

In other words, after estimation of the L -multipath directional set in DOA Estimation Unit 112 for j -th source, the received signals at the antenna elements are appropriately weighted as given in the equation (32).

This process is repeated for all J signal sources received at the antenna elements with each source signal weighted by coefficients corresponding to L -multipaths.

Referring now to **Fig. 4**, a block diagram illustrating an example computer system suitable for hosting a software implementation of the DOA Estimation unit **112** and Beamforming unit **114**, is shown. As illustrated, computing device **400** includes one or more processors **402**, system memory **404**, mass storage devices **406**, other I/O devices **408** and network communication interface **410**, coupled to each other via system bus **412** as shown.

Processor **402** is employed to execute software implementations of DOA Estimation **112** and/or Beamforming **114**. Processor **402** may be any one of a number of processors known in the art or to be designed. Examples of suitable processors include but are not limited microprocessors available from Intel Corp of Santa Clara, CA.

System memory **404** is employed to store working copies of Estimation **112** and/or Beamforming **114** and operating system services. System memory **404** may be Dynamic Random Access Memory (DRAM), Synchronous DRAM (SDRAM) or other memory devices of the like.

Mass storage devices **406** are employed to persistently store data, including e.g. a persistent copy of Estimation **112** and/or Beamforming **114**. Examples of mass storage devices **406** include but are not limited to hard disks, CDROM, DVDROM, and so forth.

Other I/O devices **408** are employed to facilitate other aspects of input/output. Examples of other I/O devices **408** include but are not limited to keypads, cursor control, video display and so forth.

Network communication interface **410** is employed to facilitate network communication with other devices. Network communication interface **410** may be wired based or wireless. In various embodiments, network communication interface **410** may support any one of a wide range of networking protocols.

In alternate embodiments, computing system may be a multi-processor systems, a cluster of networked computers, including an array of massively parallel computing nodes.

5 Accordingly, various novel methods and apparatus for determining the DOA of J signals, and/or determining the DOA of L multipaths of J signals, the J signals being wireless transmitted by their sources.

 While the present invention has been described in terms of the foregoing embodiments, those skilled in the art will recognize that the invention is not limited
10 to the embodiments described. Other embodiments may be practiced with modification and alteration within the spirit and scope of the appended claims. Accordingly, the description is to be regarded as illustrative instead of restrictive.

CLAIMS

What is claimed is:

- 5 1. In a system, a method of operation comprising:
 - receiving a first plurality of signals wirelessly transmitted by a plurality of
 - signal sources, employing a plurality of sensors;
 - taking a first sample of the received signals sensed by the sensors;
 - constructing a first received signal vector based on the first sample,
 - 10 employing a first plurality of signal directional vectors; and
 - determining a first plurality of directions of arrival for the signals based at
 - least in part on a relationship between the first received signal vector and the first
 - plurality of signal directional vectors.
2. The method of claim 1, wherein
 - 15 the plurality of signals comprise J signals wirelessly transmitted by J
 - corresponding signal sources with center frequency f_0 , the J signals traveling at
 - speed c and impinging on the sensors from directions of arrival $\theta_1 \dots \theta_J$;
 - said receiving comprises receiving the J signals employing N sensors with
 - spacing d , where N is an integer greater than 1, and
 - 20 said constructing of a first received signal comprises constructing a first
 - received signal vector ($\mathbf{x}(t)$) given by

$$\mathbf{x}(t) = \mathbf{A}\mathbf{s}(t) + \mathbf{n}(t)$$

where

$$\mathbf{x}(t) = [x_1(t), \dots, x_J(t)]^T$$

$$\mathbf{A} = [\mathbf{a}(\theta_1), \dots, \mathbf{a}(\theta_J)]$$

$\mathbf{a}(\theta_j) = [1 \ e^{-ikd \cos \theta_j} \ \dots \ e^{-i(N-1)kd \cos \theta_j}]^T$, $j = 1, \dots, J$, are the signal

directional vectors,

$\mathbf{s}(n) = [s_1(n), \dots, s_J(n)]^T$ are complex envelopes of outputs at the

sensors, and

$$k = 2\pi f_0 / c.$$

3. The method of claim 2, wherein said determining of a first plurality of directions of arrival for the signals comprises determining $\theta_1 \dots \theta_L$ based at least in part on $\mathbf{a}(\theta_i)$ for $i = 1 \dots J$ intersecting with a subspace spanned by the first $\mathbf{x}(t)$.

4. The method of claim 3, wherein said determining of the first plurality of directions of arrival for the signals further comprises computing

a first coefficient $r_{11} = \|\mathbf{x}(t)\|$, and

a first orthonormal vector $\mathbf{q}_1 = \frac{\mathbf{x}(t)}{r_{11}}$.

5. The method of claim 4, wherein said determining of a first plurality of directions of arrival for the signals further comprises computing for $\mathbf{a}(\sim \theta_i)$

a second coefficient $r_{12} = \mathbf{q}_1^H \mathbf{a}(\sim \theta_i)$,

a second orthonormal vector $\mathbf{q}_2 = \mathbf{a}(\sim \theta_i) - r_{12} \mathbf{q}_1$, and

a third coefficient $r_{22} = \|\mathbf{q}_1^H \mathbf{a}(\sim \theta_i)\|$,

where $\sim \theta_i$ is a trial value for $\theta_1 \dots \theta_J$.

6. The method of claim 5, wherein said determining of a first plurality of directions of arrival for the signals further comprises evaluating a function $B(\theta) = \frac{1}{r_{22}}$ for $\sim \theta_i$, and determining whether the evaluation yields a peak value

for the function.

7. The method of claim 6, wherein said determining of a first plurality of directions of arrival for the signals further comprises repeating said computing, evaluating and determining whether the evaluation yields a peak value for the function, for J or more $\mathbf{a}(\sim \theta_i)$, and setting J peak values as $\theta_1 \dots \theta_J$.
- 5 8. The method of claim 1, wherein said determining of a first plurality of directions of arrival for the signals comprises determining the first plurality of directions of arrival based at least in part on the first plurality of signal directional vectors intersecting with a subspace spanned by the first received signal vector.
9. The method of claim 1, wherein the method further comprises
10 taking a second sample of the received signals sensed by the sensors;
constructing a second received signal vector based on the second sample,
employing a second plurality of signal directional vectors; and
determining a second plurality of directions of arrival for the signals based
at least in part on a relationship between the second received signal vector and
15 the second plurality of signal directional vectors.
10. The method of claim 9, wherein the method further comprises determining a third plurality of directions of arrival based at least in part on corresponding averages of the first and second plurality of directions of arrival.
11. In a system, a method of operation comprising:
20 receiving a plurality of signals wireless transmitted by a plurality of signal sources, employing a plurality of sensors;
determining a first plurality of directions of arrival for a first plurality of multipaths of a first of the signals; and

obtaining the first received signal based at least in part on the determined first plurality of directions of arrival for the first plurality of multipaths of the first signal.

12. The method of claim 11, wherein

5 the method further comprises determining a second plurality of directions of arrival for the signals; and

said determining of the first plurality of directions of arrival for the first plurality of multipaths of the first signal comprises searching for the first plurality of directions of arrival for the first plurality of multipaths of the first signal in a
10 direction range centered on the determined direction of arrival of the first signal.

13. The method of claim 11, wherein

the method further comprises determining a correlation matrix for the signals, and determining a plurality of eigenvectors of the correlation matrix corresponding to the signals; and

15 said determining of the second plurality of directions of arrivals for the signals, including the direction of arrival of the first signal, is performed based at least in part on the determined eigenvectors of the correlation matrix corresponding to the signals.

14. The method of claim 13, wherein said determining of the correlation matrix
20 comprises averaging a plurality of sets of outer-products of a plurality of signal plus noise vectors determined based on a plurality of corresponding snapshots of the signals sensed by the sensors.

15. The method of claim 11, wherein

said receiving of a plurality of signals comprises receiving J signals wirelessly transmitted by J signal sources, employing N sensors, where J and N are integers, each greater than 1;

the j th transmitted signal is modeled as $x_j(t) = s_j(t)e^{j(2\pi(2+\phi_0))}$, $s(t)$ being

5 a base band signal, and ϕ_0 being an initial phase; and

the received j th signal is given by $\mathbf{x}_j(t) = \sum_{l=1}^L R_{jl} e^{i2\pi(f_d \cos \theta_{jl} - f\tau_{jl})} s(t - \tau_{jl})$

where R_{jl} is the signal strength of the l 'th multipath of the j 'th signal,

$f_d \cos \theta_{jl}$ is a Doppler shift the l 'th multipath of the j 'th signal,

f is a carrier frequency,

10 $s(\cdot)$ is a base band signal,

$\tau_{jl} = r_{jl}/c$ is a time delay of the l 'th multipath of the j 'th signal,

r_{jl} is a range of the l 'th multipath of the j 'th signal,

c is speed of Electromagnetic wave, and

θ_{jl} is the direction of arrival of the l 'th multipath of the j 'th signal.

15 16. The method of claim 15, wherein

a response vector at the N sensor for a signal impinging from an angle θ is

given by $\mathbf{v}(\theta_{jl}) = [1 \ e^{-\frac{i2\pi \cos \theta_{jl}}{\lambda}} \ e^{\frac{i4\pi \cos \theta_{jl}}{\lambda}} \ \dots \ e^{\frac{i2\pi(N-1)\cos \theta_{jl}}{\lambda}}]^T$; and

a baseband signal vector corresponding to the l 'th multipath of the j 'th signal impinging from an angle θ_{jl} is given by

20 $\mathbf{x}_j(t) = \sum_{l=1}^L \mathbf{v}(\theta_{jl}) R_{jl} e^{i2\pi(f_d \cos \theta_{jl} - f\tau_{jl})} s(t - \tau_{jl})$.

17. The method of claim 16, wherein said searching comprises computing for a search vector $\{\mathbf{v}(\theta_{jk_1}), \mathbf{v}(\theta_{jk_2}), \dots, \mathbf{v}(\theta_{jk_L})\}$, θ_{jk_l} being a search angle,

$$r_{11} = \|\mathbf{v}(\theta_{jk_1})\|_2 \text{ and}$$

$$\mathbf{q}_1 = \frac{\mathbf{v}(\theta_{jk_1})}{r_{11}}$$

$\|\cdot\|_2$ is the 2-norm of the vector.

18. The method of claim 17, wherein said searching further comprises computing

$$r_{il} = \mathbf{q}_i^H \mathbf{v}(\theta_{jk_l}); \quad 1 \leq i \leq l-1; \quad l = 2, \dots, L+1$$

$$5 \quad r_{ll} = \left\| \mathbf{v}(\theta_{jk_l}) - \sum_{i=1}^{l-1} r_{il} \mathbf{q}_i \right\|_2, \quad l = 2, \dots, L+1, \text{ and}$$

$$\mathbf{q}_l = [\mathbf{v}(\theta_{jk_l}) - \sum_{i=1}^{l-1} r_{il} \mathbf{q}_i] / r_{ll}, \quad l = 2, \dots, L+1.$$

19. The method of claim 18, wherein said searching further comprises determining whether a function $B(\Theta_j) = \frac{1}{r_{L+1,L+1}}$ yields a peak value, and if so,

setting $\Theta_j = \{\theta_{j1}, \dots, \theta_{jL}\}$ as the first directions of arrival of the first plurality of

10 multipaths of the first signal.

20. The method of claim 11, wherein said obtaining of the first received signal comprises obtaining $z(t)$ based on the determined directions of arrival of L -multipaths of the first received signal as follows

$$z(t) = \sum_{l=1}^L \sum_{n=1}^N x_n w_{nl} \quad \text{where} \quad w_{nl} = e^{-ikd(n-1)\cos\hat{\theta}_{jl}}$$

15 21. An apparatus comprising:

storage medium having stored therein programming instructions designed to enable the apparatus to

construct a first received signal vector employing a first plurality of

signal directional vectors; based at least in part on a first sample of a

plurality of received signals wirelessly transmitted by a plurality of
 signal sources, received employing a plurality of sensors; and
 determine a first plurality of directions of arrival for the signals based at
 least in part on a relationship between the first received signal vector
 and the first plurality of signal directional vectors; and
 at least one processor coupled to the storage medium to execute the
 programming instructions.

22. The apparatus of claim 21, wherein

the plurality of signals comprise J signals wirelessly transmitted by J
 corresponding signal sources with center frequency f_0 , the J signals traveling at
 speed c and impinging on the sensors from directions of arrival $\theta_1 \dots \theta_J$;

the J signals are received employing N sensors with spacing d , where N is
 an integer greater than 1, and

the programming instructions are designed to perform said constructing of
 a first received signal by constructing a first received signal vector ($\mathbf{x}(t)$) given by

$$\mathbf{x}(t) = \mathbf{A}\mathbf{s}(t) + \mathbf{n}(t)$$

where

$$\mathbf{x}(t) = [x_1(t), \dots, x_J(t)]^T$$

$$\mathbf{A} = [\mathbf{a}(\theta_1), \dots, \mathbf{a}(\theta_J)]$$

$$\mathbf{a}(\theta_j) = [1 \quad e^{-ikd \cos \theta_j} \quad \dots \quad e^{-i(N-1)kd \cos \theta_j}]^T, \quad j = 1, \dots, J, \quad \text{are the signal}$$

directional vectors,

$$\mathbf{s}(n) = [s_1(n), \dots, s_J(n)]^T \quad \text{are complex envelopes of outputs at the}$$

sensors, and

$$k = 2\pi f_0 / c.$$

23. The apparatus of claim 22, wherein the programming instructions are
 designed to perform said determining of a first plurality of directions of arrival for

the signals by determining $\theta_1 \dots \theta_L$ based at least in part on $\mathbf{a}(\theta_i)$ for $i = 1 \dots J$ intersecting with a subspace spanned by the first $\mathbf{x}(t)$.

24. The apparatus of claim 23, wherein the programming instructions are further designed to perform as part of said determining, computing of

5 a first coefficient $r_{11} = \|\mathbf{x}(t)\|$, and
a first orthonormal vector $\mathbf{q}_1 = \frac{\mathbf{x}(t)}{r_{11}}$.

25. The apparatus of claim 24, wherein the programming instructions are designed to perform as part of said determining, computing for $\mathbf{a}(\sim \theta_i)$

a second coefficient $r_{12} = \mathbf{q}_1^H \mathbf{a}(\sim \theta_i)$,
10 a second orthonormal vector $\mathbf{q}_2 = \mathbf{a}(\sim \theta_i) - r_{12} \mathbf{q}_1$, and
a third coefficient $r_{22} = \|\mathbf{q}_1^H \mathbf{a}(\sim \theta_i)\|$,
where $\sim \theta_i$ is a trial value for $\theta_1 \dots \theta_J$.

26. The apparatus of claim 25, wherein the programming instructions are designed to perform as part of said determining, evaluation of a function

15 $B(\theta) = \frac{1}{r_{22}}$ for $\sim \theta_i$, and determination of whether the evaluation yields a peak
value for the function.

27. The apparatus claim 26, wherein the programming instructions are designed to perform as part of said determining, repeating of said computing, evaluation and determination of whether the evaluation yields a peak value for the
20 function, for J or more $\mathbf{a}(\sim \theta_i)$, and setting of J peak values as $\theta_1 \dots \theta_J$.

28. The apparatus of claim 21, wherein the programming instructions are designed to perform as part of said determining, determination of the first plurality

of directions of arrival based at least in part on the first plurality of signal directional vectors intersecting with a subspace spanned by the first received signal vector.

29. The apparatus of claim 21, wherein the programming instructions are
5 designed to perform

construction of a second received signal vector based on the second sample, employing a second plurality of signal directional vectors, based at least in part on a second sample of the received signals sensed by the sensors; and

determination of a second plurality of directions of arrival for the signals
10 based at least in part on a relationship between the second received signal vector and the second plurality of signal directional vectors.

30. The apparatus of claim 29, wherein the programming instructions are further designed to enable the apparatus to determine a third plurality of directions of arrival based at least in part on corresponding averages of the first and second
15 plurality of directions of arrival.

31. An apparatus comprising:

storage medium having a plurality of programming instructions designed to enable the apparatus to

determine a first plurality of directions of arrival for a first plurality of

20 multipaths of a first of a plurality of signals wireless transmitted by a plurality of signal sources, and received employing a plurality of sensors, and

obtain the first received signal based at least in part on the determined first plurality of directions of arrival for the first plurality of multipaths
25 of the first signal; and

at least one processor coupled to the storage medium to execute the programming instructions.

32. The apparatus of claim 31, wherein

the programming instructions are further designed to enable the apparatus to determine a second plurality of directions of arrival for the signals; and

the programming instructions are designed to perform said determining of the first plurality of directions of arrival for the first plurality of multipaths of the first signal by searching for the first plurality of directions of arrival for the first plurality of multipaths of the first signal in a direction range centered on the determined direction of arrival of the first signal.

33. The apparatus of claim 31, wherein

the programming instructions are further designed to enable the apparatus to determine a correlation matrix for the signals, and determine a plurality of eigenvectors of the correlation matrix corresponding to the signals; and

the programming instructions are designed to perform said determining of the second plurality of directions of arrivals for the signals, including the direction of arrival of the first signal, based at least in part on the determined eigenvectors of the correlation matrix corresponding to the signals.

34. The apparatus of claim 33, wherein the programming instructions are

designed to perform said determining of the correlation matrix by averaging a plurality of sets of outer-products of a plurality of signal plus noise vectors determined based on a plurality of corresponding snapshots of the signals sensed by the sensors.

35. The apparatus of claim 31, wherein

said receiving of a plurality of signals comprises receiving J signals wirelessly transmitted by J signal sources, employing N sensors, where J and N are integers, each greater than 1;

the j th transmitted signal is modeled as $x_j(t) = s_j(t)e^{j(2\pi(2+\varphi_0))}$, $s(t)$ being

5 a base band signal, and φ_0 being an initial phase; and

the received j th signal is given by $\mathbf{x}_j(t) = \sum_{l=1}^L R_{jl} e^{i2\pi(f_d \cos \theta_{jl} - f\tau_{jl})} s(t - \tau_{jl})$

where R_{jl} is the signal strength of the l 'th multipath of the j 'th signal,

$f_d \cos \theta_{jl}$ is a Doppler shift the l 'th multipath of the j 'th signal,

f is a carrier frequency,

10 $s()$ is a base band signal,

$\tau_{jl} = r_{jl}/c$ is a time delay of the l 'th multipath of the j 'th signal,

r_{jl} is a range of the l 'th multipath of the j 'th signal,

c is speed of Electromagnetic wave, and

θ_{jl} is the direction of arrival of the l 'th multipath of the j 'th signal.

15 36. The apparatus of claim 35, wherein

a response vector at the N sensor for a signal impinging from an angle θ is

given by $\mathbf{v}(\theta_{jl}) = [1 \ e^{-\frac{i2\pi \cos \theta_{jl}}{\lambda}} \ e^{\frac{i4\pi \cos \theta_{jl}}{\lambda}} \ \dots \ e^{\frac{i2\pi(N-1)\cos \theta_{jl}}{\lambda}}]^T$; and

a baseband signal vector corresponding to the l 'th multipath of the j 'th signal impinging from an angle θ_{jl} is given by

20 $\mathbf{x}_j(t) = \sum_{l=1}^L \mathbf{v}(\theta_{jl}) R_{jl} e^{i2\pi(f_d \cos \theta_{jl} - f\tau_{jl})} s(t - \tau_{jl})$.

37. The apparatus of claim 36, wherein the programming instructions are

designed to perform as part of said searching, computation for a search vector

$\{\mathbf{v}(\theta_{jk_1}), \mathbf{v}(\theta_{jk_2}), \dots, \mathbf{v}(\theta_{jk_L})\}$, θ_{jk_i} being a search angle,

$r_{11} = \|\mathbf{v}(\theta_{jk_1})\|_2$ and

$$\mathbf{q}_1 = \frac{\mathbf{v}(\theta_{jk_1})}{r_{11}}$$

$\|\cdot\|_2$ is the 2-norm of the vector.

38. The apparatus of claim 37, wherein the programming instructions are designed to perform as part of said searching, computation of

$$r_{il} = \mathbf{q}_i^H \mathbf{v}(\theta_{jk_l}); \quad 1 \leq i \leq l-1; \quad l = 2, \dots, L+1$$

$$r_{ll} = \left\| \mathbf{v}(\theta_{jk_l}) - \sum_{i=1}^{l-1} r_{il} \mathbf{q}_i \right\|_2, \quad l = 2, \dots, L+1, \text{ and}$$

$$\mathbf{q}_l = [\mathbf{v}(\theta_{jk_l}) - \sum_{i=1}^{l-1} r_{il} \mathbf{q}_i] / r_{ll}, \quad l = 2, \dots, L+1.$$

39. The apparatus of claim 38, wherein the programming instructions are designed to perform as part of said searching, determination of whether a function

$$B(\Theta_j) = \frac{1}{r_{L+1, L+1}} \text{ yields a peak value, and if so, set } \Theta_j = \{\theta_{j1}, \dots, \theta_{jL}\} \text{ as the first}$$

directions of arrival of the first plurality of multipaths of the first signal.

40. The apparatus of claim 31, wherein the programming instructions are designed to perform said obtaining of the first received signal by obtaining $z(t)$ based on the determined directions of arrival of L -multipaths of the first

received signal as follows

$$z(t) = \sum_{l=1}^L \sum_{n=1}^N x_n w_{nl} \quad \text{where} \quad w_{nl} = e^{-ikd(n-1)\cos\hat{\theta}_{jl}}$$

41. A system comprising:

a plurality of antennas to receive a plurality of signals wirelessly transmitted by a plurality of signal sources;

a RF unit coupled to the antennas to down convert the received signals;
and

a direction of arrival estimation unit coupled to the RF unit, to

construct a first received signal vector employing a first plurality of

5 signal directional vectors; based at least in part on a first sample of
the received signals; and

determine a first plurality of directions of arrival for the signals based at
least in part on a relationship between the first received signal vector
and the first plurality of signal directional vectors.

10 42. The system of claim 41, wherein the direction of arrival estimation unit
performs as part of said determination, determination of the first plurality of
directions of arrival based at least in part on the first plurality of signal directional
vectors intersecting with a subspace spanned by the first received signal vector.

43. The system of claim 41, wherein the direction of arrival estimation unit
15 further

constructs a second received signal vector employing a second plurality of
signal directional vectors, based at least in part on a second sample of the
received signals; and

20 determines a second plurality of directions of arrival for the signals based at
least in part on a relationship between the second received signal vector and the
second plurality of signal directional vectors.

44. The apparatus of claim 43, wherein the direction of arrival estimation unit
further determines a third plurality of directions of arrival based at least in part on
corresponding averages of the first and second plurality of directions of arrival.

45. A system comprising:

a plurality of antennas to receive a plurality of signals wirelessly transmitted by a plurality of signal sources;

a RF unit coupled to the antennas to down convert the received signals;

5 and

a direction of arrival estimation unit coupled to the RF unit, to

determine a first plurality of directions of arrival for a first plurality of multipaths of a first of a plurality of received signals wireless transmitted by a plurality of signal sources, and

10 obtain the first received signal based at least in part on the determined first plurality of directions of arrival for the first plurality of multipaths of the first signal.

46. The system of claim 45, wherein the direction of arrival estimation unit further

15 determines a second plurality of directions of arrival for the signals; and determines the first plurality of directions of arrival for the first plurality of multipaths of the first signal by searching for the first plurality of directions of arrival for the first plurality of multipaths of the first signal in a direction range centered on the determined direction of arrival of the first signal.

20 47. The system of claim 45, wherein the direction of arrival estimation unit further

determines a correlation matrix for the signals, and determines a plurality of eigenvectors of the correlation matrix corresponding to the signals; and

determines the second plurality of directions of arrivals for the signals, including the direction of arrival of the first signal, based at least in part on the determined eigenvectors of the correlation matrix corresponding to the signals.

48. The system of claim 47, wherein the direction of arrival estimation unit

5 determines the correlation matrix by averaging a plurality of sets of outer-products of a plurality of signal plus noise vectors determined based on a plurality of corresponding snapshots of the received signals.

49. An article of manufacture comprising

a machine readable medium having stored therein a plurality of

10 programming instructions designed to enable an apparatus to be able to

construct a first received signal vector employing a first plurality of

signal directional vectors; based at least in part on a first sample of a

plurality of received signals wirelessly transmitted by a plurality of

sources; and

15 determine a first plurality of directions of arrival for the signals based at

least in part on a relationship between the first received signal vector

and the first plurality of signal directional vectors.

50. The article of claim 49, wherein the programming instructions are designed

to perform as part of said determination, determination of the first plurality of

20 directions of arrival based at least in part on the first plurality of signal directional vectors intersecting with a subspace spanned by the first received signal vector.

51. An article of manufacture, comprising

a machine readable medium having stored therein a plurality of

programming instructions designed to enable an apparatus to

determine a first plurality of directions of arrival for a first plurality of
multipaths of a first of a plurality of received signals wireless
transmitted by a plurality of signal sources, and
obtain the first received signal based at least in part on the determined
5 first plurality of directions of arrival for the first plurality of multipaths
of the first signal.

52. The article of claim 51, wherein the programming instructions are further
designed to enable the apparatus to
determine a second plurality of directions of arrival for the signals; and
10 determine the first plurality of directions of arrival for the first plurality of
multipaths of the first signal by searching for the first plurality of directions of
arrival for the first plurality of multipaths of the first signal in a direction range
centered on the determined direction of arrival of the first signal.