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GPS Compass: A Novel Navigation Equipment

A GPS (Global Positioning System)-based compass is designed, which consists of three parts: the pointer, the sensor, and the controller. Using the carrier phase signals from GPS satellites, the 1 m long pointer equipped with two GPS receivers can aim to the desired direction with accuracy less than one degree. A baseline rotation method is proposed to resolve the problem of integer ambiguities. The classical antenna swap method is simply a special case of the rotation method. The rotating character of the compass provides the convenient environment for applying the turning technique. Such compass may replace the traditional heading devices in navigation systems, such as the magnetic compasses or gyroscopes.

I. INTRODUCTION

The heading indicator of a vehicle is one of the most important devices in navigation systems, such as the magnetic compasses, gyroscopes, etc. The accuracy of the magnetic compass is affected by the magnetic field intensity nearby the equipment. To keep the magnetic compass away from the iron ore (underground), iron materials, electrical machines, electric magnetic waves, etc. is very difficult in general. On the other hand, the gyroscopes suffer from the error drift. The measurement noises of gyroscopes may be modeled by a random process, whose variance is proportional to the operation time duration. Compared with the above two devices, the proposed Global Positioning System (GPS) compass can point to any desired direction, without the above-mentioned shortcomings.

The GPS compass includes three parts: the pointer, the sensor, and the controller. The pointer is a mechanical structure which can aim to any given direction in a horizontal plane. The sensor contains two GPS receivers which can provide L1 carrier phase information. The Magnavox MX4200 receivers are used in our experiments. The controller consists of a personal computer (e.g., 486), a stepping motor, and the interface cards. The baseline of the pointer in our experiments is chosen to be 1 m long, which may be altered with different equipment. There are two operation modes of the GPS compass: initialization mode and normal mode. During the initialization mode, a 30 deg or larger rotation is performed in order to resolve cycle ambiguities problems and to find the phase adjustments. With the compensated phase adjustments computed at the end of initialization, the real-time azimuth angle can be determined in the normal mode, by using the double difference method. The stepping motor then turns the pointer to the desired direction.

In the process, the algorithms for the attitude determination by using GPS L1 carrier phase data are developed. Similar algorithms using the idea of interferometry have been developed in many works, e.g. [1, 3, 7, 8], and the references therein. In attitude determination with the GPS carrier phase, the "cycle ambiguity" is the most important problem to be solved. Ambiguity functions, time difference, and space difference are typical approaches to deal with this problem. In our approach, a baseline rotation method is proposed based on the concept of space difference, in which the baseline vector is turned for a specific angle. The true direction vector is computed from the double differences of the phase observables obtained before and after the rotation. With the algorithms developed and the experimental setup, the accuracy of azimuth is 1 deg by our experimental results. Noting that the receivers used in our experiments are low-end receivers, the performance can be better if more advanced receivers are adopted.

The paper is organized as follows. In Section II, the GPS carrier phase model and differentials are introduced. Section III discusses the classical antenna

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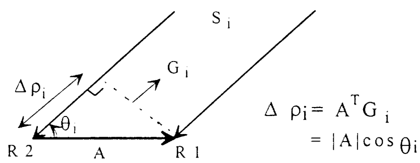

Fig. 1. Attitude determination via GPS carrier phase.

swap method and the newly designed baseline rotation method. Section IV then describes the GPS compass setup, and some experimental results. The paper is concluded with Section V.

II. DOUBLE DIFFERENCE METHOD OF GPS CARRIER PHASE

Attitude determination using GPS to meet certain accuracy specifications requires taking the carrier phase measurements from different receivers and different satellites. Consider the configuration shown in Fig. 1. Let R1 and R2 denote two GPS antennas which receive the signals from the same GPS satellite denoted by *Si*. The goal is to determine the direction of the vector A relative to some reference frame. Assume that the positions of the two antennas are close to each other, so that the directional unit vector to the satellite G_i for the two receivers are the same. If the length of the vector is known, it is then necessary to find the difference between the distances from the two antennas to the satellite, i.e., $\Delta\rho_i$. Better measurement gives rise to better angle measurement θ_i between the vector A and the direction vector G_i.

The following notations are adopted in the following discussions.

$\phi^i_{1\mathrm{m}}(\phi^i_{2\mathrm{m}})$	Carrier phase observables of receiver 1 (receiver 2) from the ith GPS satellite.
$\rho^i_1(\rho^i_2)$	Distance between the ith GPS satellite and receiver 1 (receiver 2).
C	Speed of light.
Δt^i	Clock bias between the clock of the ith GPS satellite and the GPS time.
$\Delta T_1(\Delta T_2)$	Clock bias between the clock of receiver 1 (receiver 2) and the GPS time.
λ	Wavelength of L1 carrier phase (= 19.03 cm).
$N^i_1(N^i_2)$	Ambiguity of the carrier phase measurement of receiver 1 (receiver 2) from the ith GPS satellite.
d^i_{ion}	Ionospheric delay between the ith GPS satellite and the receivers.
d^i_{trop}	Tropospheric delay between the ith GPS satellite and the receivers.
$\mathrm{bias}^i_1(\mathrm{bias}^i_2)$	Bias of the carrier phase measurement of receiver 1 (receiver 2) due to the antenna phase center variation, multipath, and other unknown factors.

Note that the ionospheric delay and the tropospheric delay are assumed to be the same for two receivers, due to the fact that the two antennas are closely located. With the above notations, the carrier phase measurements can be modeled as

$$\lambda \cdot \phi^i_{1m} = \rho^i_1 + C(\Delta t^i - \Delta T_1) + \lambda \cdot N^i_1 - d^i_{\mathrm{ion}} + d^i_{\mathrm{trop}} + \mathrm{bias}^i_1 \qquad (1)$$

$$\lambda \cdot \phi^i_{2m} = \rho^i_2 + C(\Delta t^i - \Delta T_2) + \lambda \cdot N^i_2 - d^i_{\mathrm{ion}} + d^i_{\mathrm{trop}} + \mathrm{bias}^i_2. \qquad (2)$$

A. Single Difference of GPS Carrier Phase

To eliminate the biases and the errors, it is necessary to perform the differences between the received observables. First, we subtract (2) from (1) to eliminate Δt^i, d^i_{ion} and d^i_{trop}, and obtain

$$\lambda \cdot (\phi^i_{1m} - \phi^i_{2m}) = \Delta\rho_i - C \cdot \Delta T + \lambda \cdot \Delta N_i + \Delta\mathrm{bias}_i \qquad (3)$$

where $\Delta\rho_i (= \rho^i_1 - \rho^i_2)$ denotes the difference between the distance ρ^i_1 and ρ^i_2, $\Delta T (= \Delta T_1 - \Delta T_2)$ is the clock bias difference between receiver 1 and 2, $\Delta N_i (= N^i_1 - N^i_2)$ is the ambiguity difference between receiver 1 and 2 with respect to the same satellite i, and $\Delta\mathrm{bias}_i (= \mathrm{bias}^i_1 - \mathrm{bias}^i_2)$ represents the difference between the biases of carrier phase measurements between receiver 1 and 2. Equation (3) can be further rewritten as

$$\Delta\rho_i = \lambda \cdot (\phi^i_{1m} - \phi^i_{2m}) + C \cdot \Delta T - \lambda \cdot \Delta N_i - \Delta\mathrm{bias}_i. \qquad (4)$$

From Fig. 1 and (4), we have the following expression,

$$A^T G_i = \Delta\rho_i = (\Delta\phi^i_m + \Delta m_i + \Delta b_i)\lambda + C \cdot \Delta T \qquad (5)$$

where $\Delta\phi^i_m \equiv \phi^i_{1m} - \phi^i_{2m}$, $\Delta m_i \equiv -\Delta N_i$, and $\Delta b_i \equiv -\Delta\mathrm{bias}_i/\lambda$.

B. Double Differences of GPS Carrier Phase

Single difference between receivers gets rid of the errors from the satellite. On the other hand, to eliminate the errors caused by the receivers, the differences between satellites must be taken. From (5), four single difference equations can be obtained from four different satellite signals. By subtracting one single difference equation from the others to eliminate $C\,\Delta T$, three double difference equations can be obtained as follows

$$A^T(G_i - G_1) = [(\Delta\phi^i_m - \Delta\phi^1_m) + (\Delta m_i - \Delta m_1) + (\Delta b_i - \Delta b_1)]\lambda = (\nabla\Delta\phi^i_m + \nabla\Delta m_i + \nabla\Delta b_i)\lambda, \quad i = 2,3,4 \qquad (6)$$

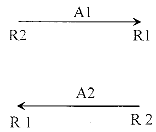

Fig. 2. Antenna swap method.

where $\nabla\Delta^i_m \equiv \Delta\phi^i_m - \Delta\phi^1_m$, $\nabla\Delta m_i \equiv \Delta m_i - \Delta m_1$, and $\nabla\Delta b_i \equiv \Delta b_i - \Delta b_1$. Define the variables

$$k_i \equiv (\nabla\Delta\phi^i_m + \nabla\Delta m_i + \nabla\Delta b_i)\lambda, \qquad i = 2,3,4$$

$$K^T \equiv [k_2 \quad k_3 \quad k_4]$$

$$G \equiv [G_2 - G_1 \quad G_3 - G_1 \quad G_4 - G_1].$$

From (6) we have

$$A^T G = K^T \tag{7}$$

which implies

$$A = G^{-T} K. \tag{8}$$

Recall that the goal is to find the direction of A, which can be calculated from the above double difference equations of GPS carrier phase. However, although $\nabla\Delta\phi^i_m$ can be obtained from the measurements of GPS receivers, the integer ambiguities and the biases are still unknown. To deal with this ambiguity problems in double difference, various methods have been developed, which include the ambiguity function method, time-difference scheme, and space-difference scheme. In the next section, the baseline rotation method is discussed, which includes the classical antenna swap technique as a special case.

III. BASELINE ROTATION METHOD

The baseline rotation method is essentially a space-difference scheme to handle the ambiguity problem. In this section, the antenna swap technique is first introduced. See Fig. 2. Before the swap, the direction vector is denoted by $A1$, which becomes $A2$ after the swap of the antennas. Obviously, we have $A2 = -A1$. From (8), $A1$ can be expressed as

$$A1 = G^{-T}\begin{bmatrix} \nabla\Delta\phi^2_m + \nabla\Delta m_2 + \nabla\Delta b_2 \\ \nabla\Delta\phi^3_m + \nabla\Delta m_3 + \nabla\Delta b_3 \\ \nabla\Delta\phi^4_m + \nabla\Delta m_4 + \nabla\Delta b_4 \end{bmatrix}\lambda$$

$$\equiv G^{-T}\begin{bmatrix} \nabla\Delta\phi_2 \\ \nabla\Delta\phi_3 \\ \nabla\Delta\phi_4 \end{bmatrix}\lambda \tag{9}$$

where $\nabla\Delta\phi_2$, $\nabla\Delta\phi_3$, $\nabla\Delta\phi_4$ denote the true double difference of carrier phases before swapping. Assuming that there is no cycle slip during the process of the swap, the vector $A2$ is then

$$A2 = G^{-T}\begin{bmatrix} \nabla\Delta^{2\prime}_m + \nabla\Delta m_2 + \nabla\Delta b_2 \\ \nabla\Delta^{3\prime}_m + \nabla\Delta m_3 + \nabla\Delta b_3 \\ \nabla\Delta^{4\prime}_m + \nabla\Delta m_4 + \nabla\Delta b_4 \end{bmatrix}\lambda$$

$$= -A1 = G^{-T}\begin{bmatrix} -\nabla\Delta\phi_2 \\ -\nabla\Delta\phi_3 \\ -\nabla\Delta\phi_4 \end{bmatrix}\lambda \tag{10}$$

where $\nabla\Delta\phi^{i\prime}_m$, $i = 2,3,4$, denote the double differences of the carrier phase measurements after swapping. Define

$$A1_m \equiv G^{-T}\begin{bmatrix} \nabla\Delta\phi^2_m \\ \nabla\Delta\phi^3_m \\ \nabla\Delta\phi^4_m \end{bmatrix}\lambda$$

$$= G^{-T}\begin{bmatrix} \nabla\Delta\phi_2 - \nabla\Delta m_2 - \nabla\Delta b_2 \\ \nabla\Delta\phi_3 - \nabla\Delta m_3 - \nabla\Delta b_3 \\ \nabla\Delta\phi_4 - \nabla\Delta m_4 - \nabla\Delta b_4 \end{bmatrix}\lambda \tag{11}$$

and

$$A2_m \equiv G^{-T}\begin{bmatrix} \nabla\Delta\phi^{2\prime}_m \\ \nabla\Delta\phi^{3\prime}_m \\ \nabla\Delta\phi^{4\prime}_m \end{bmatrix}\lambda$$

$$= G^{-T}\begin{bmatrix} -\nabla\Delta\phi_2 - \nabla\Delta m_2 - \nabla\Delta b_2 \\ -\nabla\Delta\phi_3 - \nabla\Delta m_3 - \nabla\Delta b_3 \\ -\nabla\Delta\phi_4 - \nabla\Delta m_4 - \nabla\Delta b_4 \end{bmatrix}\lambda. \tag{12}$$

By taking the difference between $A1_m$ and $A2_m$, the ambiguities can be deleted, which yields

$$(A1_m - A2_m)/2 = G^{-T}\begin{bmatrix} \nabla\Delta\phi^2_m - \nabla\Delta\phi^{2\prime}_m \\ \nabla\Delta\phi^3_m - \nabla\Delta\phi^{3\prime}_m \\ \nabla\Delta\phi^4_m - \nabla\Delta\phi^{4\prime}_m \end{bmatrix}\lambda/2$$

$$= G^{-T}\begin{bmatrix} \nabla\Delta\phi_2 \\ \nabla\Delta\phi_3 \\ \nabla\Delta\phi_4 \end{bmatrix}\lambda = A1. \tag{13}$$

As a result, the true direction vector $A1$ can be obtained.

The operation of antenna swapping can be thought of as rotating the baseline vector by an angle of 180 deg. It is thus suspected that we may rotate the baseline vector by some other angles to assist us in dealing with the ambiguity problems. The baseline rotation method thus evolves and is discussed next.

Let the baseline axis be rotated by an angle θ as shown in Fig. 3. Letting

$$\text{BIAS} \equiv G^{-T}\begin{bmatrix} -\nabla\Delta m_2 - \nabla\Delta b_2 \\ -\nabla\Delta m_3 - \nabla\Delta b_3 \\ -\nabla\Delta m_4 - \nabla\Delta b_4 \end{bmatrix}\lambda \tag{14}$$

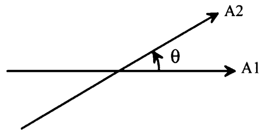

Fig. 3. Baseline rotation method.

from the definitions in (11) and (12), we have

$$A1_m = A1 + \mathrm{BIAS}$$
$$A2_m = A2 + \mathrm{BIAS}. \tag{15}$$

The relation between $A1$ and $A2$ can be observed from Fig. 3 as

$$A2 = R(\mathbf{n},\theta)A1 \tag{16}$$

where $R(\mathbf{n},\theta)$ denotes the rotation about an axis $\mathbf{n}$ by an angle θ. For the current setup, the baseline vector is rotated in the horizontal plane, so the rotation axis $\mathbf{n} = [0\ 0\ 1]^T$. In other words, the rotation axis is Z-axis in the user frame, which leads to rotation matrix

$$R(\mathbf{n},\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{17}$$

From (15), the biases can be eliminated, which yields

$$A2_m - A1_m = A2 - A1 = R(\mathbf{n},\theta)A1 - A1$$
$$= [R(\mathbf{n},\theta) - I_{3\times3}]A1. \tag{18}$$

With measured $A2_m$, $A1_m$, and the known angle, the true $A1$ can be then computed. However, noting that the matrix $[R(\mathbf{n},\theta) - I_{3\times3}]$ is singuler, the generalized inverse technique [4] needs to be used to find $A1$. By singular value decomposition (SVD)

$$[R(\mathbf{n},\theta) - I_{3\times3}] = U \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & 0 \end{bmatrix} V^T \tag{19}$$

the generalized inverse of $[R(\mathbf{n},\theta) - I_{3\times3}]$ can be obtained as

$$[R(\mathbf{n},\theta) - I_{3\times3}]^+ = V \begin{bmatrix} 1/\sigma_1 & 0 & 0 \\ 0 & 1/\sigma_2 & 0 \\ 0 & 0 & 0 \end{bmatrix} U^T.$$

Accordingly,

$$\tilde{A1} = V \begin{bmatrix} 1/\sigma_1 & 0 & 0 \\ 0 & 1/\sigma_2 & 0 \\ 0 & 0 & 0 \end{bmatrix} U^T(A2_m - A1_m). \tag{20}$$

From (20), the first and second elements of $\tilde{A1}$ are the same as those of $A1$, but the third element is zero. This means that the method can be only applied to 2-dimensional attitude determination. However, if there is one more rotation about another orthogonal axis, the third component can be computed. With such arrangement, the 3-dimensional attitude determination can be accomplished.

Compared with the antenna swap method, the baseline rotation method proposed above allows smaller angles of turning. This may be required due to space limitations in applications. But the a ngle cannot be too small either. Later experiments show that the rotation angles larger than 30 deg lead to sound results.

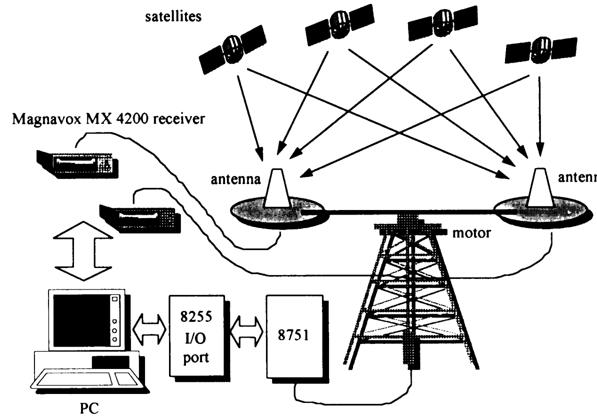

Fig. 4. GPS compass.

IV. GPS COMPASS

By using the algorithms discussed above, the GPS compass is designed. The rotating character of the compass provides a convenient environment to take the advantage of the baseline turning method. The configuration of the proposed GPS compass is shown in Fig. 4.

The compass system contains three main parts: the pointer, the sensor, and the controller. The pointer realizes the baseline vector which is made by an aluminum beam. The sensor part includes two GPS receivers with antennas attached to the right and left tip of the aluminum beam, respectively. Two metal plates are placed under the GPS antennas to reduce the effect of multipath. The beam is rotated by a stepping motor which is controlled by a personal computer. The controller part consists of the computer, the algorithm, and the stepping motor. The principle of operation is roughly described as follows. First, the initialization mode is started. The computer receives the signals from two GPS receivers and computes the current attitude. To complete the baseline rotation method in the process, the computer needs to be able to control the stepping motor, in which the 8255 I/O port, 8751 single chip, and the external interrupt technique are used. After the algorithm gives the current direction, the phase measurement adjustments are computed. This complete the initialization mode, whose flow chart is shown in Fig. 5.

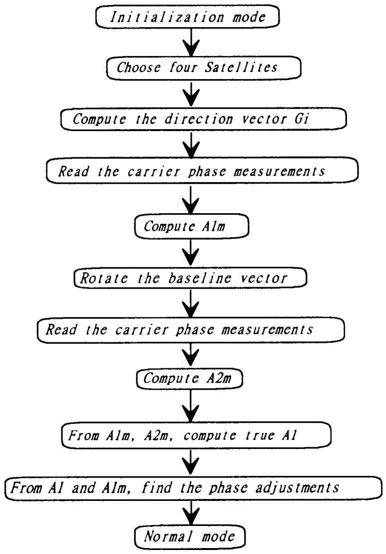

Fig. 5. Initialization mode.

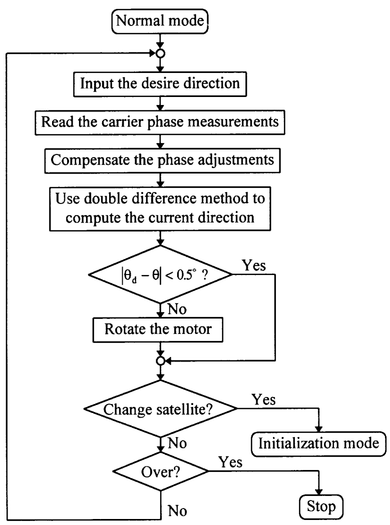

Fig. 6. Normal mode.

After the success in the initialization mode, the normal mode follows. The algorithm accepts the input from the user for the desired pointing direction. With the adjustment values computed in the initialization mode, the compass is able to calculate the difference between the current attitude and the desired attitude by using double difference scheme. The system then issues the commands to the motor to have the beam point to the requested direction. If some disturbances do occur, the compass can also immediately discern the change and control the motor to meet the specified requirement. The flow chart for the normal mode is depicted in Fig. 6.

Using the Magnavox 4200 receivers, the experiments were performed with rotation angle being 30 deg in the rotation method. The results are shown in Table I, which indicates that the accuracy of the baseline length and the azimuth angle are about 2 cm and 1 deg, respectively.

TABLE I
Experimental Results for Baseline Rotation Method With 30 Degrees Turning Angle

no.	baseline(m)	azimuth(deg)
1	1.11	0.53
2	1.10	0.79
3	1.11	0.38
4	1.10	0.23
5	1.10	1.05
6	1.11	1.18
7	1.10	0.39
8	1.12	0.43
9	1.09	1.15
10	1.11	-0.39
true value	≒1.10	≒0.00

Some other experiments have been done for different rotation angles. From our experience, the accuracy is better when the angle θ is larger. Thus larger angles should be selected. However, to save space and rotation time in some applications, the angle should not be too large. The experiments show that 30 deg is adequate for 1 deg accuracy. On the other hand, it is noted that the receivers we used are not high-end receivers. The accuracy may be better if better receivers can be adopted.

V. CONCLUSION

With the concept of space difference, the baseline rotation method using GPS carrier phase messages for single-axis attitude determination was explored. The algorithm successfully resolves the problem of cycle ambiguities. Combining the algorithm and the motor controller, a novel direction-finding device, the GPS compass, is designed. From the experimental results, the accuracy of pointing is about 1 deg with our setup, which can be improved with better equipment. The GPS compass may compensate or replace the traditional equipments of pointing devices in the future.

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To Implement the CDMA Multiuser Detector by Using Transiently Chaotic Neural Network

To design suboptimal CDMA multiuser detector is a hot topic. We propose to implement the CDMA multiuser detector by using transiently chaotic neural network (TCNN). After going through a transiently chaotic process, the network reaches the global optimum or the neighbor of global optimum. Computer simulation results show that the proposed detector is clearly superior to Hopfield neural network (HNN) based detector and comparable with the optimal detector.

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I. INTRODUCTION

Because of multiple access interference and channel noise, the conventional method [1] of demodulating a spread-spectrum signal in a multiuser environment which employed one matched filter to the desired signal is not reliable and sensitive to near-far effect. For this reason there has been an interest in designing optimal receivers for various multiuser communication systems [7, 8]. However, Berdu proved that the optimal multiuser detection is a NP-complete problem [2]. Hence, there is a necessity for the development of suboptimal receivers which are robust to near-far effects and have a lower computational complexity and comparable bit-error-rate (BER) performance. Multistage detector (MSD) proposed by Varanasi and Aazhang [9] is a well-known suboptimal scheme.

On the other hand, the massive parallelism of neural networks makes them desirable for solving various complex tasks. Paris, et al. proposed a feedforward neural network based multiuser detector (FNN–MD) [3]. While their detectors are shown to be very good for a very small number of users, the complexity of FNN–MD appears to be exponential in the number of users, and as well known, the number of neurons in the hidden layer is not easy to determine. Kechriotis, et al. [4] investigated the application of Hopfield neural networks (HNNs) on the design of optimal multiuser detector and presented a HNN-based detector (HNN–MD), which can produce in real time suboptimal solutions. HNN–MD is essentially equivalent to an infinite number of stages MSD. But, as pointed out by [3], the growth of the number of the local minimum of the objective function and the degradation of the performance of HNN–MD as the number of users increases.

In this work, we apply the transiently chaotic neural network (TCNN) to design the optimal CDMA multiuser detector. In Section II, the problem to be studied is introduced. A new neural network based multiuser detector is proposed in Section III. In Section IV the performance of the proposed detector is evaluated by the computer simulations. Finally, in Section V the conclusion is presented.

II. MULTIUSER DETECTION

Assume that in a given time interval $[0,T)$ there are K active transmitters sharing the same Gaussian channel. In the general CDMA system, the signal at a given receiver is the superposition of the K transmitted signals in additive channel noise

$$r(t) = \sum_{i=-P}^{P}\sum_{k=1}^{K} b_k^{(i)} S_k(t - iT - \tau_k) + n_t \quad t \in R$$