A New Cross Layer MAC Protocol Design for MIMO Ad Hoc Networks

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Abstract— **In this paper, first we give an overview of decision feedback multiuser detector and spatial multiplexing system operating at the physical layer. After that, we introduce a new mac protocol and describe in detail the proposed policies for channel access and traffic management. The whole process is driven in order to guarantee a satisfactory throughput and yet protect the wanted signals through active interference detection and cancellation. Results show that our protocol provides a large throughput improvement. This is due to the higher number of packets delivered to their final destination.**

Keywords- MIMO, ad hoc networks, cross layer MAC protocool design, multiuser detection

I. INTRODUCTION

An ad hoc wireless network is a collection of wireless nodes that self-configure to form a network without the aid of any established infrastructure. Some or possibly all of these nodes are mobile. These networks are extremely compelling for applications where a communications infrastructure is too expensive to deploy, cannot be deployed quickly, or is simply not feasible. There are numerous potential applications for ad-hoc wireless networks, ranging from multihop wireless broadband Internet access, to sensor networks, to building or highway automation, to voice and video communication for disaster areas [1]-[7].

Ad hoc networks are harder to design than wired networks because of problems that arise from the every nature of wireless communication. One of these problems, namely the hidden terminal that makes collision. To avoid collisions, a collision avoidance method could be used, as in the well known IEEE 802.11 DCF.

A networking-based approach is carried out in [5] with MIMA-MAC, an access protocol specifically designed for ad hoc networks with up to two antennas per node. The small number of nodes considered and the constraint to use at most one antenna for transmission represent significant limitations.

In [6], a centralized controller is able to estimate concurrent resource usage and to schedule links to exploit the benefits of MIMO such as Spatial Multiplexing (SM) and interference suppression, along with increased transmit rate. This last contribution, although interesting, makes some very strong assumptions on the PHY layer, e.g., that any transmission uses the full channel capacity and that signaling at the MAC level is perfect.

In this paper, we use MIMO technique to improve MAC in ad hoc networks. MIMO techniques allow exploiting the presence of multiple antennas to improve transmission bit rate through spatial multiplexing or to improve the signal decoding efficiency through diversity reception and interference cancellation. In this paper, we provide some framework and results on the reception performance of MIMO link in a multiuser scenario. The results show that the capture capability introduced by MIMO technology is significant and this should be taken into account when designing MAC protocols.

II. MODEL OF PHY LAYER

Consider that nodes with multiple antennas are arranged in the network where transmission takes place using packet radio communications. Transmitting nodes build streams of bits and encode them to combat channel impairments. At the receiver, multiuser decoding is performed symbol-by-symbol, with a decorrelating layered space-time signal processing technique [2]. The receiver is listening to the signals coming from K different users, $l = 1,...,K$, each using u_l antennas, and thus has to decode a total of $U = \sum_{l=1}^{K} u_l$ incoming symbol per time interval. Let $b = [b_1,...,b_U]^T$ denote the symbol vector where each element is a symbol coming from one of the U transmitting antennas. Let S be a matrix with columns containing spreading sequences, one column for each stream. Signals pass through the fading channel that we assume to be frequency non-selective, represented by the channel matrix $H = [h_1,...,h_P]$, where h_p is $1 \times K$ channel coefficient vector between the p-th receiver antenna and all K users. The received signal at antenna p can be written as:

$$r_p = SC_p b + n_p \qquad (1)$$

where C_p denotes the complex diagonal channel matrix for the p-th antenna, $diag(h_a)$ .The noise vector n_p is a complex valued zero mean Gaussian random N-vector with a covariance matrix $\sigma^2 I_N$, in which I_N denotes the $N \times N$ identity matrix, where N is length of spreading code for each user. After the space code match filtering, we obtain the sufficient statistics vector Y_{MU} as:

$$Y_{MU} = \sum_{p=1}^{P} X_p^H r_p = R_{MU} b + n \qquad (2)$$

Where $X_p = SC_p$ is cross-correlation matrix. The sufficient statistics vector in (2) becomes a sum of two contributions, the first coming from decoded signals, and the other representing a interference term, namely

$$Y_{MU} = \sum_{p=1}^{P} X_p^H (r_p + X_p^{\text{int}} b_{\text{int}}) = R_{MU} b + n + I \qquad (3)$$

Where $I = \sum_{p=1}^{P} X_p^H X_p^{\text{int}} b_{\text{int}}$ is the space filtered interfering signal. We report in Fig. 1 a flowchart description of detection algorithm. The complete description of the base of this algorithm is available in [2] to the interested reader.

In Fig. 2, we report a graph of bit error rate for all combinations of 4, 10, 14, 16 and 22 users with one antenna each and a receiver with 6 and 8 antennas. Fig. 2 suggests that the loss in spectral efficiency due to the use of BPSK is easily recovered by the higher decoding performance of the system. For instance, with 14 incoming streams the BER for BPSK falls bellow 10^{-5} for 10dB SNR. Note that in a more realistic ad hoc network scenario, where the nodes are randomly placed in the area of network, the different average received powers that result would lead to even better performance.

We showed in [9] and [10] more results for PHY layer simulation.

III. CROSS LAYER MAC DESIGN

The IEEE 802.11 protocol includes a specific mode called ad hoc. This mode operates according to the so-called Distributed Coordination Function (DCF). In turn, DCF defines two different modes, the basic mode (with random access after carrier sensing) and the collision avoidance mode (with four-way handshaking before channel access). We know that preventing collisions would result in loss of data and waste of resource. In this section we want to introduce a good solution for hidden terminal problem in ad hoc network. With some channel knowledge, obtained through training sequences, receiver detects incoming streams separately. Each node have a limited capability of N_S^{max} sequence simultaneously. So the protocol must be aware of the tradeoff existing between the among of wanted data to detect and the interference protection granted to this data.

In our approach, we consider that channel of nodes with a certain distance from receiver can be detected and cancelled and nodes with further distance and low received power can not be cancelled.

We use a framed communication structure, with four phases. Theses phases are designed according to standard sequence of messages in a collision avoidance mechanism, and are summarized as follows.

Sending RTS packet: In this phase, all senders look into their backlog queue, and if it is not empty they compose transmission requests and pack them into a single RTS message. Each packet in the queue is split into multiple streams of fixed length, such that each stream can be transmitted through one antenna. Any RTS has to specify the number of streams to be sent simultaneously, in addition to the intended destination node. How to associate a destination node with a suitable number of transmit antenna depends on the degree of spatial multiplexing sought, as well as the local traffic intensity, thus the queue level of the sender. Any RTS may contain several such requests. Moreover, an RTS is always sent with one antenna and at full power. Each node selects number of antennas according to number of streams of current packet and keeps free other antennas for sending other packets.

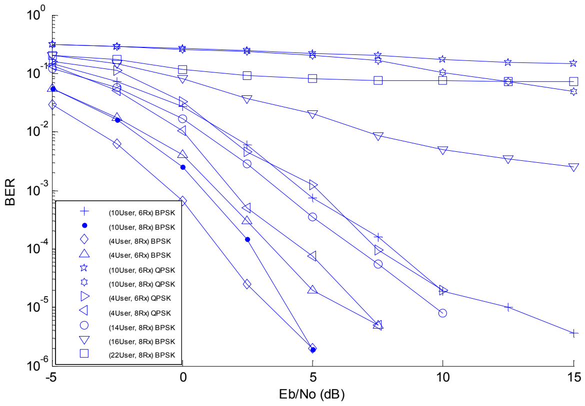

Fig. 2. Comparison of BERs as a function of SNR per receiver antennas for 4,10 users each with one antenna and 6, 8 receiver antennas using BPSK and QPSK modulations.

Sending CTS packet: During this phase, all nodes that were not transmitters, themselves receive multiple simultaneous RTSs, and apply the reception algorithm of section 2 to separate and decode them. CTSs are also sent out using one antenna and at full power. We use 4 scheme for receiving data and interferes streams to control the number of allowed transmitters and antennas.

Sending DATA packet: All transmitters receive CTSs and, after BLAST detection, they follow CTS indication and send their streams.

Sending ACK packet: After detection, all receivers evaluate which streams have been correctly received and send an ACK back to the transmitters. After the last phase the data handshake exchange is complete, the current frame ends and the next is started.

A random backoff is needed for nodes that do not receive a CTS, as otherwise persistent attempts may lead the system into deadlock [3].

To specify our MAC protocol, we need to introduce a simpler protocol for comparison. Indeed, Simpler protocol is a CSMA/CA, just using a more powerful MIMO PHY layer.

Consider that the set of neighbors of a given node s be denoted as $\mathcal{V} = \{v_1, v_2, \ldots\}$. Let a_{sv_j} be the maximum number antenna that s can uses when transmitting to any set of nodes that includes v_j. Suppose that node n is current node. At step $i = 1$, a request is created as fellows. The node reads the $k_1 = 1$ packet's destination, d_{k_1}, and the number of unsent streams, p_{k_1}. After that, node compares p_{k_1} with maximum antenna constraint, $a_{nd_{k_1}}$. If $p_{k_1} > a_{nd_{k_1}}$, the streams violate from maximum antenna constraint, hence forbidding any further spatial multiplexing. The request pair $(d_{k_1}, a_{nd_{k_1}})$ is inserted in the RTS packet.

If $p_{k_1} \le a_{nd_{k_1}}$, the pair (d_{k_1}, p_{k_1}) is inserted in the RTS. Each node keeps indices of all packets selected for transmission in set S_i. The total number of antennas allocated until step i hold in $A(i)$. In the absence of interferes, node d_{k_1}could support $a_{nd_{k_1}} - p_{k_1}$ further antenna. So, the node goes to step 2 and searches its queue , until it finds a packet k_2 that maximum number of destination's antenna match the condition $a_{nd_{k_2}} \ge A(1)$. This means that the d_{k_2}can stand the transmission of the $A(1)$ streams from other node, in addition to its own. The transmitter sets $S_2 = S_1 \cup \{k_2\}$, calculates the number of streams allocated to packet k_2 as $M(2) = min\{\min\{a_{nd_{k_1}}, a_{nd_{k_2}}\} - A(1), p_{k_2}\}$, that not violate the maximum number of antenna constraints $a_{nd_{k_1}}$ *and* $a_{nd_{k_2}}$and $A(1)$ steams have been allocated. Then , it inserts in the RTS packet the pair $(d_{k_2}, M(2))$, and finally updates $A(2) = A(1) + M(2)$. If there is still antenna for transmission without saturating antenna constraints, algorithm goes to next step and so on. In general, at step i, the node searches the queue for a packet k_i with condition $a_{nd_{k_i}} > A(i -.$ Then $S_i = S_{i-1} \cup \{k_i\}$, $M(i) = min\{min_{j\epsilon S_i} a_{nd_{k_j}} - A(i-1), p_{k_i}\}$, and $A(i) = A(i-1) + M(i)$. The request $(d_{k_i}, M(i))$ is put in the RTS. The algorithm then goes to step $i+1$ if and only if $min_{j\epsilon S_i} a_{nd_{k_j}} > A(i)$ and a packet such that $a_{nd_{k_{i+1}}} > A(i)$ is found in the queue [8]. As an example consider Fig. 3.

Rx id	Number of streams	Maximum number of antennas
8	1	4
7	2	4
13	1	8
4	1	2
15	4	8

Request 1		Request 2		Request 3		Request 4	
Rx id	streams	Rx id	streams	Rx id	streams	Rx id	streams
8	1	7	2	13	1	15	1

Fig. 3. An example of application of RTS sending scheme.

In this section we report 4 schemes for receiving data from transmitters. All of these schemes contain two set $\mathcal{W}$ and $\mathcal{U}$. The first set contains all requests directed to the node that names wanted request, the second set all other requests that names unwanted request. We knows that if p_k streams implies to transmitted, the receiver estimates channel of this streams. After that, number of available estimating resources is $N_s^{max} - p_k$. If $N_s^{max} - p_k > 0$ and exist any request in the node queue, process will be continued in the next step and so on.

SNR based receiver protocol: The node grants first highest power request in $\mathcal{W}$ and then considers all other requests in $\mathcal{W} \cup \mathcal{U}$, re-ordered by decreasing received power. In Fig. 4, an example of application of this protocol is showed.

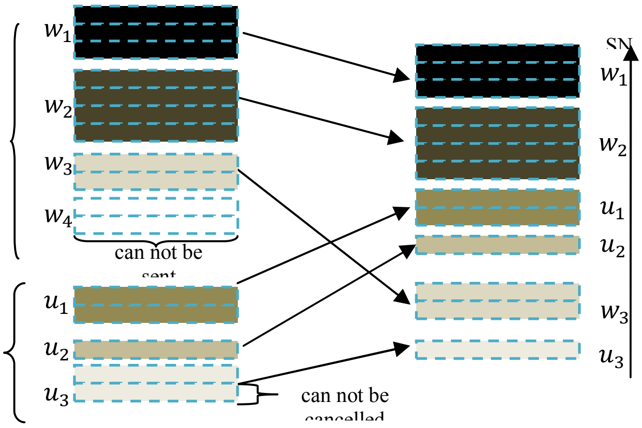

Fig. 4. An example of application of SNR based receiver protocol.

First wanted based receiver protocol: In this protocol, a node gives priority to wanted transmission. If any estimating resources left , it then begins to consider unwanted requests. In Fig. 5, an example of application of this protocol is showed.

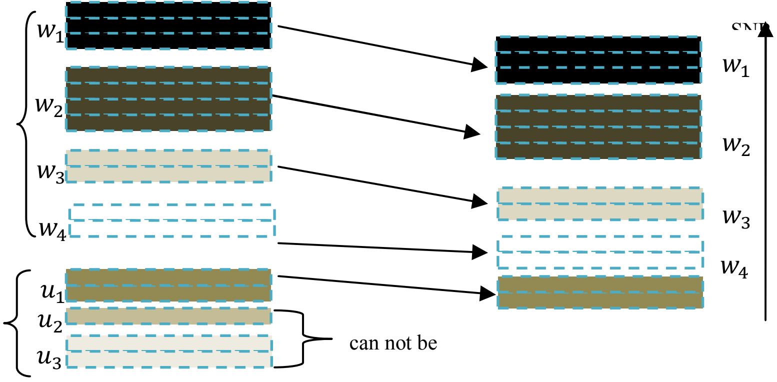

Fig. 5. An example of application of first wanted based receiver protocol.

Wanted based receiver protocol: In this case, the node grants the requests in $\mathcal{W}$ and does not consider $\mathcal{U}$ at all. In Fig 6, an example of application of this protocol is showed.

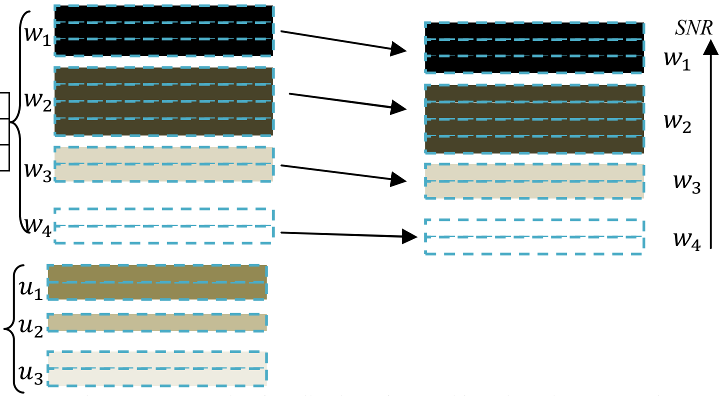

Fig. 6. An example of application of wanted based receiver protocol.

SNR based receiver protocol without interference cancellation: This scheme operates as SNR based receiver protocol, but does not perform cancellation of interfering requests in $\mathcal{U}$. It means that only powerful interferes could be considered. In Fig 7, an example of application of this protocol is showed.

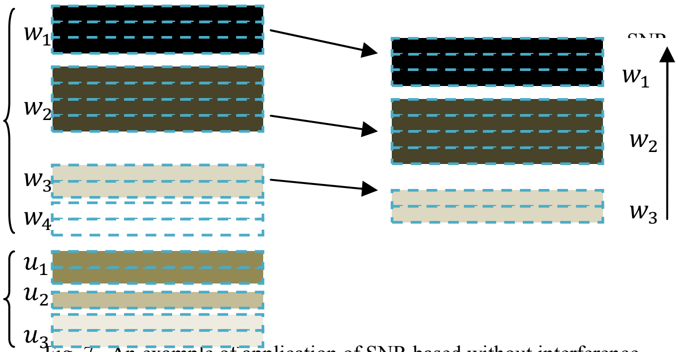

Fig. 7. An example of application of SNR based without interference cancellation receiver protocol.

CTS sending schemes are the only way to reduce data traffic in ad hoc network, since RTS/CTS are not used for channel reservation., but rather as an indication of intention /clearance to transmit, also both RTS and CTS sending schemes favor the creation of multiple point to point links, all potentially making use of SM. This is made possible by inserting multiple requests (grants) in the RTS (CTS), each composed of multiple streams. These schemes can operate on top of any PHY that successively detects multiple signals, cancels their contribution from the received signal. We choose V-BLAST as one such PHY, since it is a good representative and has recently received a lot of attention.

IV. NETWORK SIMULATION

For evaluating our MAC scheme, we deploy 25 nodes randomly in a square area with 8 antennas each and nearest neighbors 25 m apart. Traffic is generated according to a Poisson process of rate λ packets per second per node. Each generated packet is made of k 125-bytes long streams, with k randomly chosen in the set $\{1, 2, 3, \text{and } 4\}$. Unsent packets are buffered. Each node has a finite FIFO queue where the packets are stored before being served. We also study the effect of convolutional coding on data packets using the standard 802.11 code [4].

Fig. 8-a shows the average network throughput defined as a function of the offered traffic λ , defined as the number of correctly detected 125-byte streams per frame for all CTS sending schemes. We see that wanted based receiver protocol has bad performance, because it permits the sending of all requested streams and does not cancel any interferers. First wanted based receiver protocol have better performance than wanted based, because it has a way to cancel highest SNR interfering streams. In the worst case, one wanted request protected against $N_s^{max}-1$ strongest interferences and lead to best performance of SNR based receiver protocol. Fig. 8-b shows the delay. In this Fig, we see that first wanted based protocol saturates at 0.08 sec i.e. 370 frames. This is a time that a packet need to reach to head of the queue and be transmitted. We observe that other protocol reach the maximum delay value i.e. timeout.

Fig. 8-c shows the average network throughput ratio defined as the number of correctly detected 125-byte streams per frame for all CTS sending schemes. As we can see the SNR based receiver protocol reach to 90% probability of correct detection at that highest traffic. Fig. 8-d shows the average queue length . We see that first wanted based protocol because of lower throughput at network load larger than 800 does not allow sufficient packet sending. Also SNR based protocol have shorter queue length. We observe that other protocol reach to upper bound of delay. SNR based receiver protocol without interference cancellation has bad performance because it hasn't interference cancellation feature. Results show that the SNR based receiver protocol reach to best performance , as it has high throughput and throughput ratio, limited delay and queue length. In addition with [7] we assume that any node estimates channel of interfering signals and reduces effect of interferers by zero forcing and successive interference cancellation (ZF-SIC) algorithm to improve network throughput and also we assume that maximum queue length of each node is 120 packets instead of 30 packets.

V. CONCLUSIONS

In this paper, we combine MIMO multiuser detection at PHY layer with design of a protocol at MAC layer in a cross layer fashion simultaneously to have a better throughput for mobile ad hoc networks. Also average queue length is shorter than maximum length of queue, i.e., 120. Future work on this topic may be the extension to routing layer issues. Our scheme can be used on laptops that each one is considered as an ad hoc node and uses 8 antennas with 3 cm distance between two adjacent antennas.

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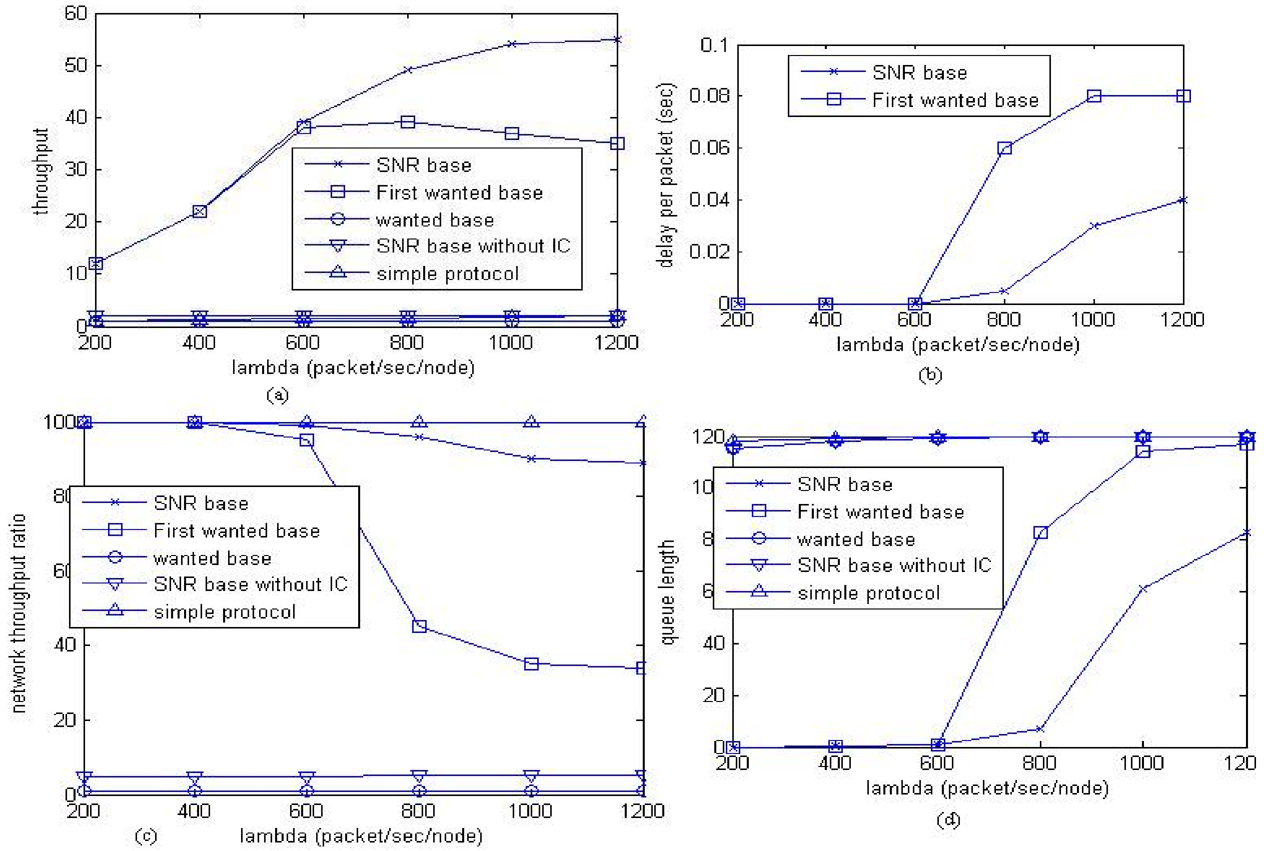

Fig. 8. (a) network throughput (b), delay per packet (c), network throughput ratio in percent and (d) queue length versus network traffic

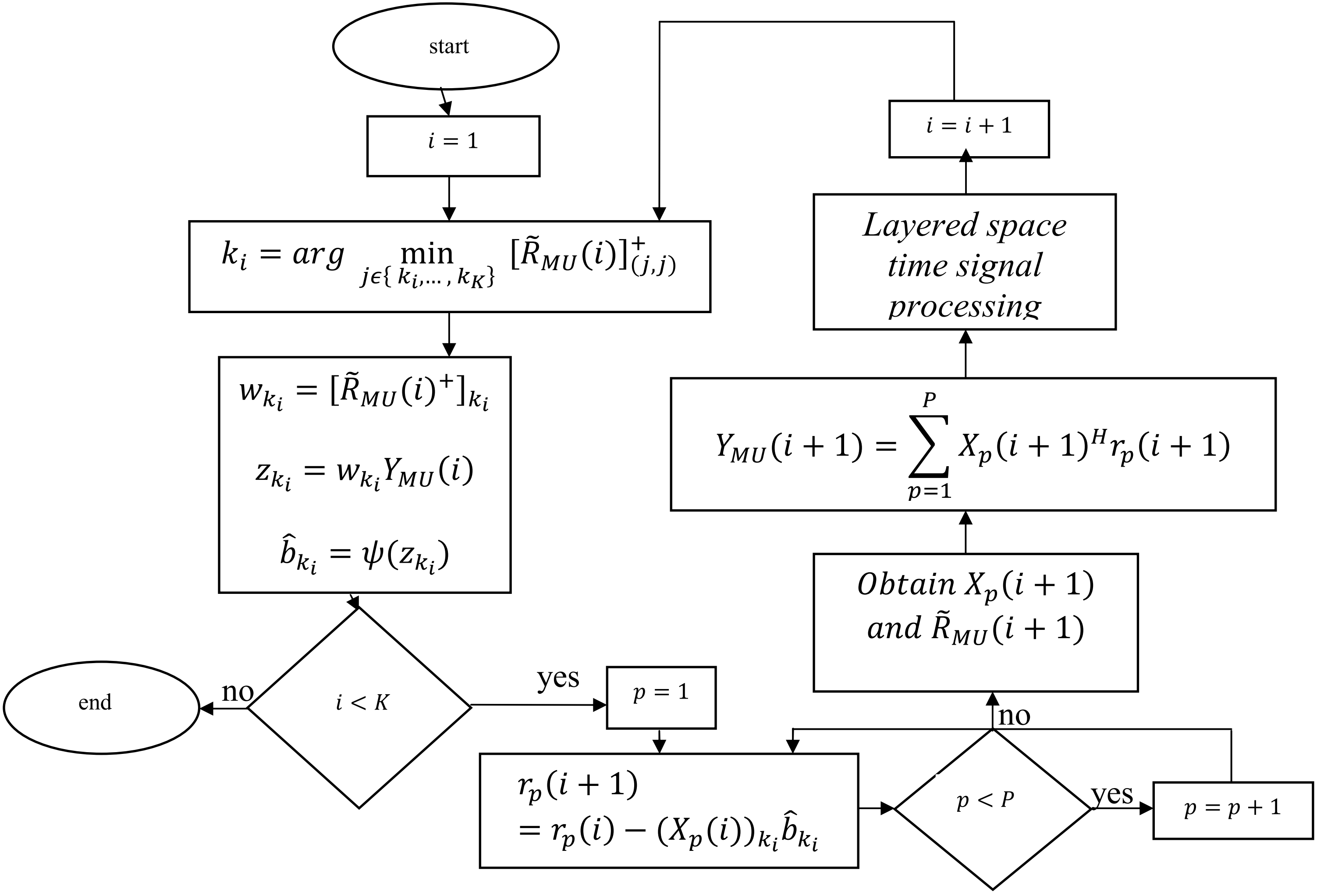

Fig. 1. flowchart description of LAyered Space Time Multi User Detection (LAST-MUD) algorithm