IEEE 802.11

Wireless Access Method and Physical Layer Specifications

TITLE: **GRAP - A Proposed Medium Access Control Protocol for Wireless Local Area Networks**

DATE: November 9, 1992

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## Abstract

A novel medium access control scheme, randomly addressed polling (RAP), for multi-cell wireless networks is proposed in this paper. RAP allows that the base stations poll successfully only knowing the active mobile nodes via distributed control but not knowing exact mobile nodes under coverage. Therefore, RAP can provide seamingless services for wireless networks with good throughput and delay performance, fairness to access, power efficiency for mobile nodes, and no handoff for data services(soft handoff for time-bounded services). In addition, practical ways to implement RAP protocol in infrastructured wireless network architecture have been proposed. Simulation results have been provided for the performance evaluation of RAP protocol. To further stablized the RAP protocol, GRAP (group RAP) has been proposd based on a superframe structure.

## I. Introduction

Personal communication services and next generation cellular communication are going to the direction of providing multiple cell network structure, even micro-cells or pico-cells. However, as the spectrum is so valuable, how to efficiently use it and provide seamless services is one of the most important issues in personal wireless communication. Among so many personal communication services, one of the hardest tasks is wireless local data communication which is under the standard effort within the IEEE project 802 toward a possible new standard, wireless local area network. In this paper, we are going to propose a new medium access control protocol — randomly addressed polling (RAP) for multi-cell wireless networks. Althouth this protocol is specifically designed to meet the requirements for wireless LAN whose medium access control protocol remains open to research community, it can be easily generalized to all kinds of wireless networks and provide attractive features such as distributed handoff, completely soft handoff, high throughput implying excellent channel utilization, simple realization complexity, and good for narrow-band and wide-band radios and infrared transmissions.

The requirements for the medium access control (MAC) protocol of wireless LANs are rather severe in the IEEE 802.11. Some of the important considerations include:

- Throughput: As the spectrum is a scare resource, the MAC protocol should utilize the spectrum very efficiently and achieve a high throughput.
- Multiple PHYs: There should be only one MAC to serve multiple physical transmission methods which may be direct-sequence spread spectrum (SS-DS), (slow) frequency-hopped spread spectrum (SS-SFH), diffused infrared, or narrow-band digital signal transmission, though they might have quite different transmission characteristics.
- Seamless Service: In the multiple-cell network environments, different from wireless voice networks, the data packets (frames) must be received correctly and can not be dropped even during the handoff(s).
- Multi-cast: According to the study of traffic in the wireless LANs, people discovered that the down-link (from network to mobile nodes) traffic dominates the whole traffic in the networks. If we consider the wireless LANs with infrastructure, such kind of down-link traffic is likely through base stations or repeaters which broadcast packets to mobile nodes. The MAC protocol must support the multi-cast function.
- Synchronous Services: The MAC should have reasonable delay statistics to support synchronous (time bounded) services other than data file transmission.
- Fairness: All the users (mobile nodes) should have equal priority to access the wireless LAN. The mobile nodes should be able to fairly register in the wireless LAN if they are qualified.
- Power Consumption: Since the mobile nodes are likely to operate by battery power, any MAC protocol to keep mobile nodes listening to base station(s) all the time should be avoided in practical applications.
- Simple to Implement: In practical applications of LAN environments, not only mobile nodes but also base stations should be kept simple implementation.

In this paper, we are confining our attention in wireless LANs (thus, wireless networks) with infrastructure. Figure 1 depicts a typical wireless (local area) network with infrastructure which consists of a wired high speed backbone network and base stations. The coverage of a base station is known as a cell in this paper. To provide seamless data services, the adjacent cells should appropriately overlap. Traditional MAC (or multiple access) protocols for wireless cellular-type networks apply complicated hand-shaking procedures to complete handoff. Within a cell, many protocol based on token passing, carrier sensing, ALOHA, have been proposed [1,5-16]. They are all facing some difficulties to be a perfect solution for wireless LANs. At the same time, a more general MAC protocol should combine multiple access and handoff into considerations. Efforts have been done in this direction [17-18]. However, all of them are designed for voice transmission and are not appropriate for MAC requirements of wireless LANs. CDMA or B-CDMA is practically hard to achieve for high rate data transmission due to the limitation of available spectrum and desirable simple base stations for LAN applications. In the following of this paper, we are going to present a new protocol to meet the MAC requirements of wireless LANs.

## II. Randomly Addressed Polling

Since the MAC of wireless LAN has to serve mobile nodes which may move across the cell boundaries, handoff initiated by a centralized scheme will make the system implementation complicated. At the same time, the dynamic nature of wireless transmission and networks makes decentralized protocol hard to work reliably. Therefore, we are proposing a centralized MAC protocol with partial decentralized functions such as initiation of handoff. Such a MAC protocol is named as randomly addressed polling (RAP). As the down-link (from backbone network to mobile nodes) transmission is obviously achieved by broadcasting, the RAP is primary aiming at the up-link traffic (from mobile nodes to network). We will discuss the whole MAC protocol in later section.

The fundamental idea of RAP is that the base stations poll those active (with packets ready to transmit) under their own coverage. Only active mobile nodes will be polled since there is no guarntee that polling all mobile nodes in the coverage of a base station can work [16]. The reason is simple. Due to the dynamic wireless channel characterisitcs and network topology, IEEE 802.11 requires that previous transmission does not imply successful transmission next time even without error caused by noise. The collection of mobile nodes under the coverage of any specific base station is not completely known by the base station. RAP protocol only intends to identify those active mobile nodes and polls those nodes. It can be carried out by the following procedure.

1. When a base station is ready to collect up-link packets, it broadcasts a message [READY] to all mobile nodes under its coverage. (It may be only a special end-of-file message from previous transmission.) Please note that the base station may not know its coverage and thus covered mobile nodes which is a realistic situation for wireless LANs due to the fast changing environments [4].

2a. For each active mobile node intending to transmit packet(s), it generates a random number from the set $I_R = \{0, 1, \cdots, p-1\}$. (Please note that this random number may be generated in advance before the reception of [READY].)

2b. All these active mobile nodes simultaneously transmit their own random numbers which are good only for one polling cycle. All these random numbers must be simultaneously transmitted orthogonally, for example, by orthogonal codes such as those for synchronous/asynchronous code division multiple access (CDMA), or by different frequency information. Furthermore, each active mobile node may generate random numbers $L$ times and transmit at $L$ stages.

2c. In general, the mobile nodes may transmit random numbers $q$ times at each stage. The base station may use majority-vote policy to decide the correctly transmitted random number(s). With error-free transmission assumed in this paper, $q = 1$ is enough. In case the base station can not recognize certain random number(s), it will assume no reception.

3. The base station listens to all multiple random addresses (at each stage) simultaneously. Suppose there are $N$ active mobile nodes. At the $l$th ($1 \leq l \leq L$) stage, there are $N$ random numbers represented by certain way which the base station can tell. Let these $N$ random numbers be $r_l^1, \cdots, r_l^N$ which may not be distinct at the $l$th stage. If no response from mobile nodes, stop this polling cycle.

4. At the $l^*$th stage, there exist most number of distinct random numbers which are $R_1 < \cdots < R_{N^*}$. Then, the base station broadcasts that it will poll according to mobile nodes' $l^*$th random number(s). When the base station polls mobile node(s) with $R_r$ ($1 \leq r \leq N^*$) at the $l^*$th stage, the mobile nodes who sent it at the $l^*$th stage transmits packet(s) to the base station. Collision is possible. If $N = N^*$, no collision exists.

5. If the base station successfully/unsuccessfully receives the packet from any mobile node, it sends a positive/negative acknowledge [PACK]/[NACK] right away before polling next one(s). If the mobile node receives [PACK], it removes the packet from its buffer. Otherwise, the mobile node(s) keep the packet(s) for future polling. After all scheduled transmissions, the base station re-polls again (repeats 1-4). Although re-polling may allow new active mobile nodes to join, we assume that no new active mobile node is allowed to join re-polling.

**Example**

Suppose there are mobile nodes A, B, C, D, E, F, G, and H under the coverage of a base station. We choose $p = 5$ and thus form a $GF(5)$. At the beginning of the polling cycle, only A, D, E, G, H are active nodes with packets to transmit. Let $L = 2$. When [READY] is received by all active nodes, A, D, E, G, H generate random numbers as follows. (step 2)

A: 3, 0
D: 2, 3
E: 2, 1
G: 1, 4
H: 1, 1

For the base station, it collects random numbers 2, 3, 4 at the first stage and numbers 0, 1, 3, 4 at the second stage if the transmission of distinct numbers can be done orthogonally. (step 3)

At the second stage, the base station can find the most distinct numbers (addresses). It polls mobile nodes according to the order of 0, 1, 3, 4. When the base station polls "0", A sends its packet. With error-free transmission, A will get [PACK] from the base station. So will D and G. However, when the base station polls "1", packets from E and H collides. Not considering the capture effect, E and H will receive [NACK] and go to re-polling procedure. (step 4 and step 5) At the same time, with the consideration of channel errors, A, D, G may get [NACK] either and join re-polling.

Repeating step 2, E and H generate random numbers as follows.

E: 4, 2
H: 3, 2

The collision can be resolved. It can be shown that the expected time to resolve collision in this RAP protocol is finite.

## III. Practical Implementation

The success of this protocol relies heavily on whether the active mobile nodes can apply appropriate orthogonal signaling to transmit the random numbers (addresses) to the base station. Since we intend to apply this MAC protocol for different transmission methods such as direct sequence spread spectrum, frequency hopped spread spectrum, narrow-band RF, and infrared with direct detect modulations, and so on, it is necessary to propose practical signaling and detection mechanisms for different transmissions. A practical random number (address) detection mechanism is shown in Figure ?. Our first problem is to find the proper signaling. The signaling scheme requires

- It is easy to detect even when the signal-to-noise ratio is not high.
- It can fit at least infrared, SS-DS, SS-SFH, and narrow-band RF.
- The detection time can not be long compared with packet length to maintain the efficiency of channel utilization.

- There exists appropriate detection scheme(s) with reasonably implementation complexity.

It is well known that many CDMA sequences have the desirable characterisitcs possibly to transmit the random numbers in RAP protocol. However, they are generally suffering from

- They are coherent sequences and not proper for infrared and SS-SFH.
- To make detection reliable, the sequence length can not be short and detection is complicated and time consuming.

Now, we introduce a kind of noncoherent sequences, prime sequences [], to meet our requirements. The construction of prime sequences is briefly summaried as follows. Let $p$ be a prime number and $GF(p) = \{0, 1, \cdots, p-1\}$ be a Galois field. A prime sequence $S_x$ is constructed by multiplying every element $j$ from $GF(p)$ with an element $x$ then modulo $p$

$$S_x = (S_{x0}, S_{x1}, \cdots, S_{xj}, \cdots, S_{x(p-1)}) \quad (1)$$

The binary prime sequence $C_x$ is obtained by the rule

$$C_x = (C_{x0}, C_{x1}, \cdots, C_{xk}, \cdots, C_{x(p^2-1)}) \quad (2)$$

where

$$C_{xk} = \begin{cases} 1, & i = S_{xj} + jp; j = 0, 1, \cdots, p-1 \\ 0, & \text{otherwise} \end{cases}$$

There are totally $p$ distinct primary prime sequences with length of $p^2$ bits generated by this rule. Based on these $p$ primary prime sequences, we can further generate another $p^2 - p$ prime sequences which are neglected due to that they are not good for asynchronous transmission. As an example, we list the primary prime sequences for $p = 5$ in the following.

$$C_0 = (10000, 10000, 10000, 10000, 10000)$$

$$C_1 = (10000, 01000, 00100, 00010, 00001)$$

$$C_2 = (10000, 00100, 00001, 01000, 00010)$$

$$C_3 = (10000, 00010, 01000, 00001, 00100)$$

$$C_4 = (10000, 00001, 00010, 00100, 01000)$$

Obviously, we can use above sequences to represent random numbers (addresses) in our proposed protocol and to provide orthogonality as their feasibility to be the noncoherent signature sequences in CDMA systems. The advantage of noncoherent sequences is that we can use noncoherent detection to decide the transmitted random numbers for all kinds of transmissions. We can use the following signaling system: transmission in a time slot as "1" and no transmission in a time slot as "0". Such a signaling system is good for infrared, SS-DS with low processing gains which are common for wireless data communication networks, SS-SFH, and narrow-band RF. Special noncoherent detection schemes can be developed by energy detection, envelope detection, etc. [20].

Another even simpler approach is to use the following sequences.

1: 10101010101010101....

2: 1001001001001001001....

3: 1000100010001000100....

4: 1000010000100001000....

0: 1000001000001000010.... or 111111111111..... (for biphse signals)

We can trace critical frequency components in above sequences to decide the transmitted random number(s) (address(es)) [20].

## IV. Performance Evaluation

We evaluate the proposed RAP protocol based on the Poisson traffic assumption. Within a unit time (packet transmission time in this paper), a mobile node has packets to transmit followed by a Poisson distribution with intensity $\lambda$. We define the throughput $\eta$ to be

$$\eta = \frac{\sigma_{succ}}{\sigma_{succ} + \sigma_{coll} + \sigma_{overhead} + \sigma_{idle}}$$

where $\sigma_{succ}$ is the time duration for successful transmission; $\sigma_{coll}$ is the time duration for collisions; $\sigma_{overhead}$ is the time duration for polling and detection overhead; $\sigma_{idle}$ is the time duration of no packet to network. We also define the time delay $D$ to be the time duration from a mobile node being active to its packet being successfully transmitted. Figure 3 to Figure 10 demonstrate the computer simulations of RAP protocol with 10 mobile nodes in a cell (the coverage of a base station). These figures show that

- The practical throughput of RAP protocol for wireless networks can be higher than 0.88 when the overhead is 0.1 packet length. We design circuits to detect the random numbers of RAP protocol. Its simulations show that 0.1 packet length is practically feasible [20]. Even we loose the overhead constraint, the RAP protocol still demonstrates satisfactory throughput and delay performance as the MAC for wireless networks.
- With more possible random numbers, though the maximum throughput is lower due to the increase of overhead length, RAP performs better in heavy traffic situations.
- Using more stages can not improve the performance due to the increase of overhead. $L = 1, 2$ are better cases for RAP protocol.

## V. More On The MAC Protocol

We have to consider extra two situations to make this protocol complete. They are joint-cell operation and down-link operation.

### Joint Cell

The mobile nodes are possibly in the joint cell region, that is, under the coverage of two or more base stations. This situation actually demonstrates the advantage of RAP protocol. When the mobile node becomes active, it only has to listen to base stations' broadcasting [READY]s. It can pick up the clearest one and follow its instructions to be polled. Handoff becomes transparent in this situation for RAP protocol. In case a mobile node moves across the joint cell or cell boundary, the RAP protocol allows this mobile node transmitting up-link packets without handoff, a novel improvement for MAC protocol for cellualr-type wireless networks. Figure 11 depicts no up-link handoff for RAP. In the joint cell, the moving active mobile node may join the polling of base station #M or that of #N according to its own choice.

### Down-Link

Up to this point, we only consider RAP protocol in up-link situations except broadcasting for down-link. However, under the multiple-cell operation, the down-link transmissions can not be fully successful via simple broadcasting since the mobile nodes may move to other cells or stay in the joint cell. We have to further modify our RAP protocol for the down-link (from the backbone network to the mobile nodes) as follows:

1. When any mobile node registers in the wireless network, a PBS (permanent base station) is assigned to store the address of CBS (current base station to cover this specific mobile node). This PBS may be the central switch for cellular networks.

2a. When a base station polls mobile nodes, it can identify itself at the same time. If a mobile node learns that it is under the coverage of a new base station, it sends a message to PBS about its new CBS. For a wireless LAN, the mobile nodes are possible to learn the change of coverage only when it becomes active. Thus, the mobile nodes do not have to monitor base stations and save power. However, if the mobile nodes require certain time-bounded services from the wireless networks such as voice in a cellualr telephone network, 2b is suggested to conduct soft handoff.

2b. Under the time-bounded services, the mobile nodes in the joint cells have to monitor the signal strength from possible base stations. A two-level handoff is suggested here.

Let $\delta_n$ be the signal strength of potentially new CBS for a mobile node in the joint cell and $\delta_c$ be the signal strength of CBS. $\delta = \delta_n - \delta_c$. If $\delta > \alpha_-$, the mobile node is ready to handoff. If $\delta > \alpha_+$, the mobile node makes a handoff.

3. Any packet intending to a mobile node goes to its PBS first. After finding the address of CBS, the packet goes to the CBS and is broadcasted. If the CBS can not get [PACK] from the destinated mobile node after some trial(s), this packet will be returned to the PBS of the mobile node.

Finally, to support multi-cast function of RAP protocol, such kind of packets will be broadcasted multiple times to ensure successful reception under channel error(s) and [PACK]s from all destinated nodes. We also would like to point out that adequate control of polling timing at base stations (such as (colored) token passing) can make RAP work smoother.

## VI. Group Randomly Addressed Polling

From the theoretical analysis of RAP protocol, we can easily observe the advantage of high efficiency when there exist very few active nodes in one random address contention cycle, that is, the number of active nodes is significantly less than $p$. Furthermore, since the down link message load is much heavier than the up-link message load, an efficient MAC protocol for wireless LANs should allocate enough transmission period for down link transmission (broadcasting). Consequently, we propose a group RAP (GRAP) protocol as shown in Figure 12 to improve the stability of RAP based on a super-frame structure similar to the superframe concept in [12].

GRAP adopts a super-frame structure consisting of $p+1$ frames. In each frame, the first part is dedicated to base station's broadcasting. Please note that each broadcasting has to consist of multiple identical transmissions to ensure precise reception for multi-casting. After the base station ensures correct reception of broadcasting, the end-of-broadcasting [EOB] is broadcast and the active nodes under its coverage know that the polling cycle begins and proceeds as previous descriptions. However, in GRAP protocol, not all active nodes compete in one contention period. The old nodes which sent transmission(s) to this base station before this cycle contend according to their previous successful random addresses and form $p-1$ groups. All the new joining nodes form the $p$th group.

In case time-bounded services (such as voice) are supported, those active nodes with time-bounded service packets can join any group for contention. To avoid possible congestion (too many packets in a superframe), time-bounded service packets may be dropped after certain delay if such an action is tolerable or may be scheduled to next (or next a few) groups. We can also observe that the down-link traffic has quite a lot more periods to broadcast.

We use an example to illustrate how GRAP works. Suppose mobile nodes A, B, C, D, E, F, G, I, K, L, are under the coverage of a base station. At the beginning of a superframe, A, C, E, K have packets to transmit whose random numbers for previous successful transmissions are 2, 3, 0, 2, respectively, and F has a time-bounded packet to transmit. After the broadcasting period, E and F are in the group "0" for contention and polling. No node is active for group "1". Then, L has a time-bounded service packet to transmit and X becomes under the coverage of the base station. A, K, L are in the group "2" now. If $p=5$, this may be a little too crowd and L's time-bounded service packet may not go through after the first try (or first a few ~~tries~~). L may defer to next group to let other packets easier to go through. Then, C and L are in the group "3". Finally, X is in the group "5".

Another version of GRAP protocol which is suitable for heavy time-bounded service traffic is to change its grouping policy. Both data packets and time-bounded service packets are arranged according to their previous random number in successful transmission. However, if data packet(s) facing certain delay in contention, it(they) reschedule(s) transmission to next superframe or later group.

## VII. Conclusions

(Group) randomly addressed polling has been shown to be an effective MAC for wireless networks with multi-cell infrastructure. Real implementation of this protocol has not begun at this moment.

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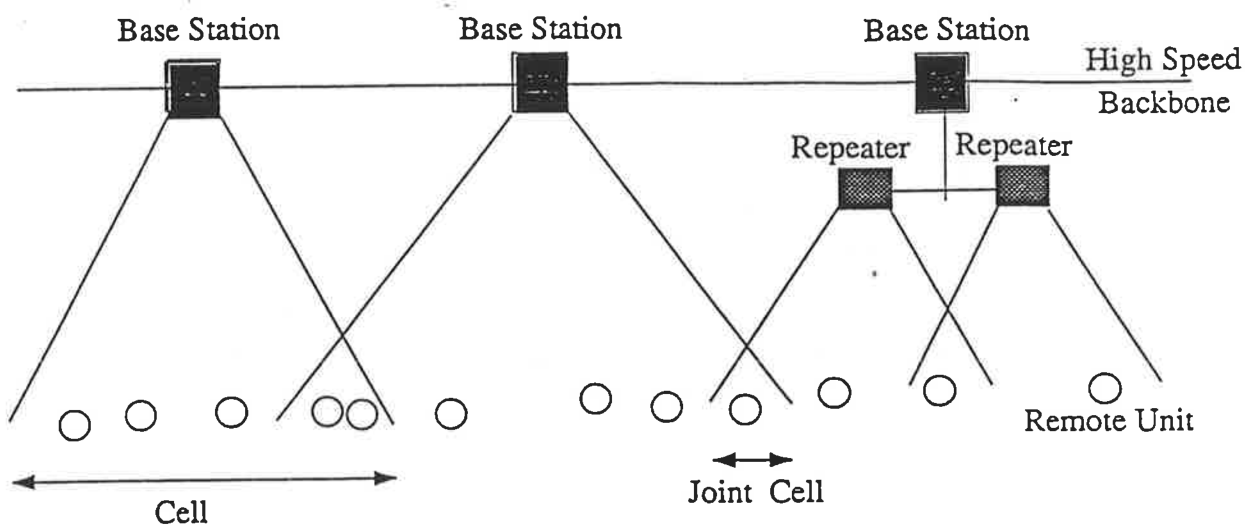



Figure 1 Wireless (Local Area) Networks with infrastructure

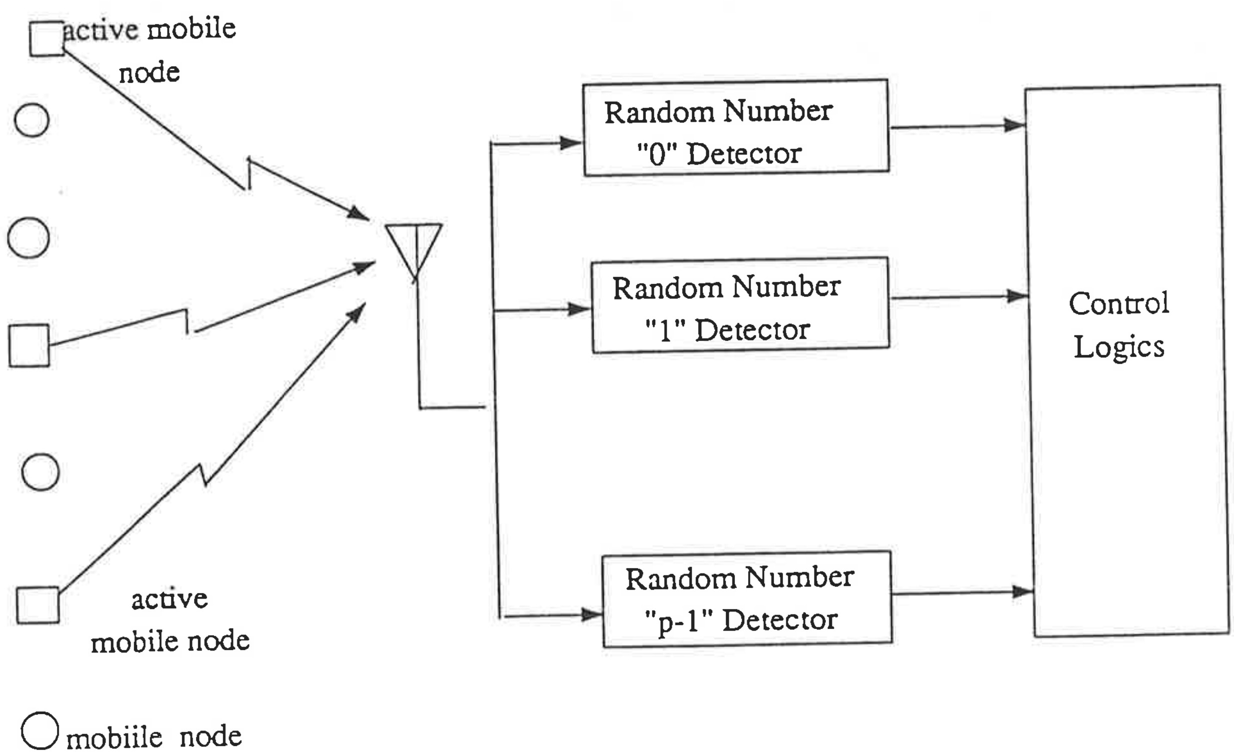



Figure 2 Multiple Random Numbers (Addresses) Detector

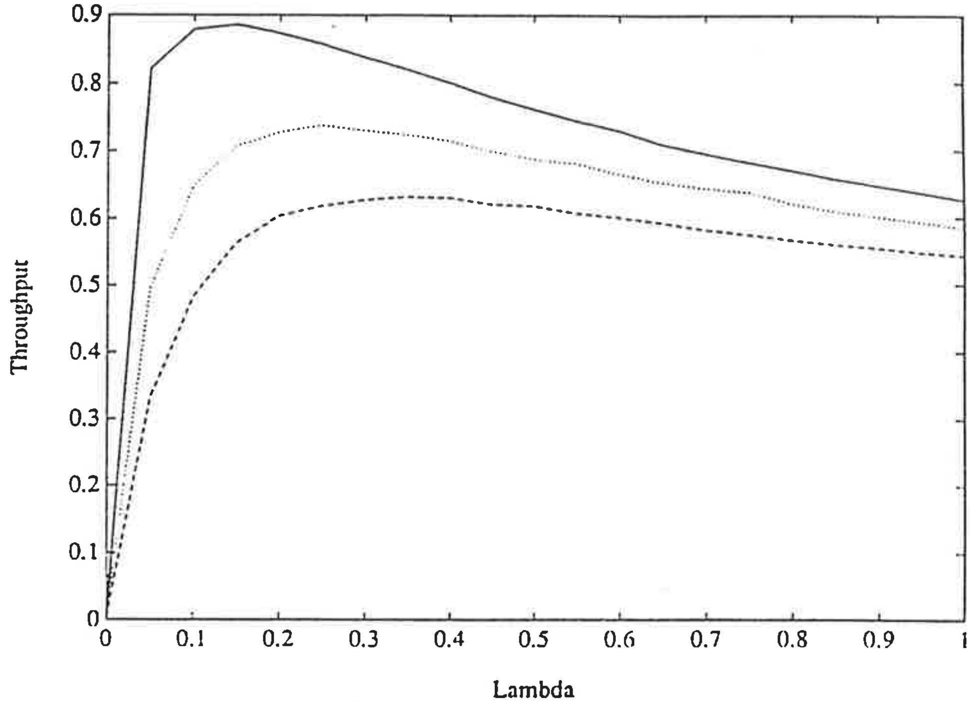



Figure 3 Throughput, 10 Mobile Nodes, L=2, p=5

Overhead Length= 0.1 (solid), 0.5 (dot), 1.0 (dash)

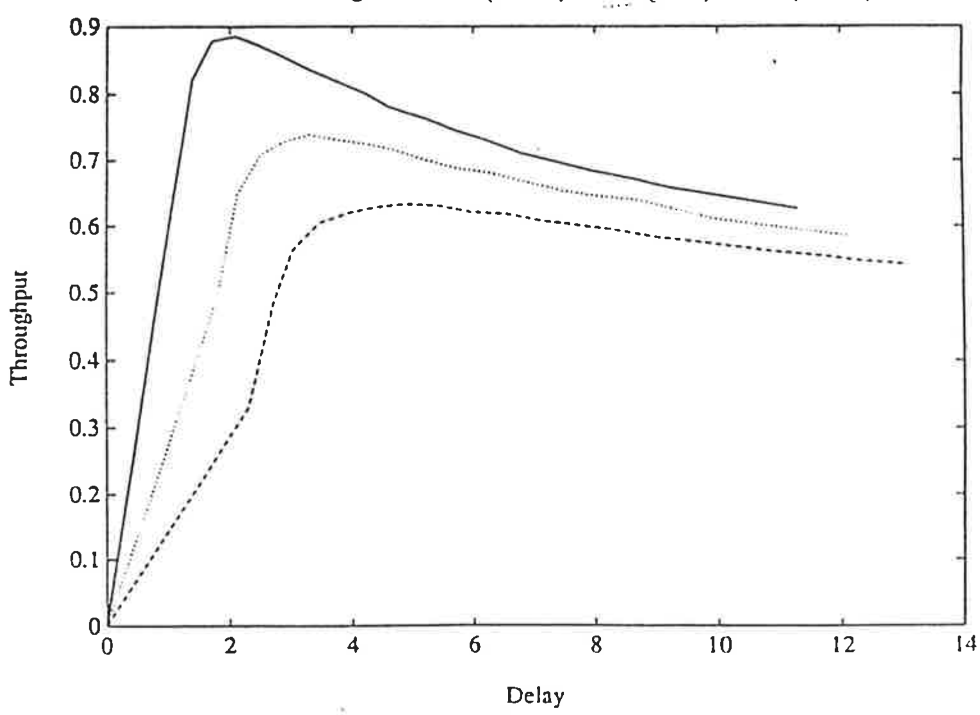



Figure 4 Delay-Throughput, 10 Mobile Nodes, L=2, p=5

Overhead Length= 0.1 (solid), 0.5 (dot), 1.0 (dash)

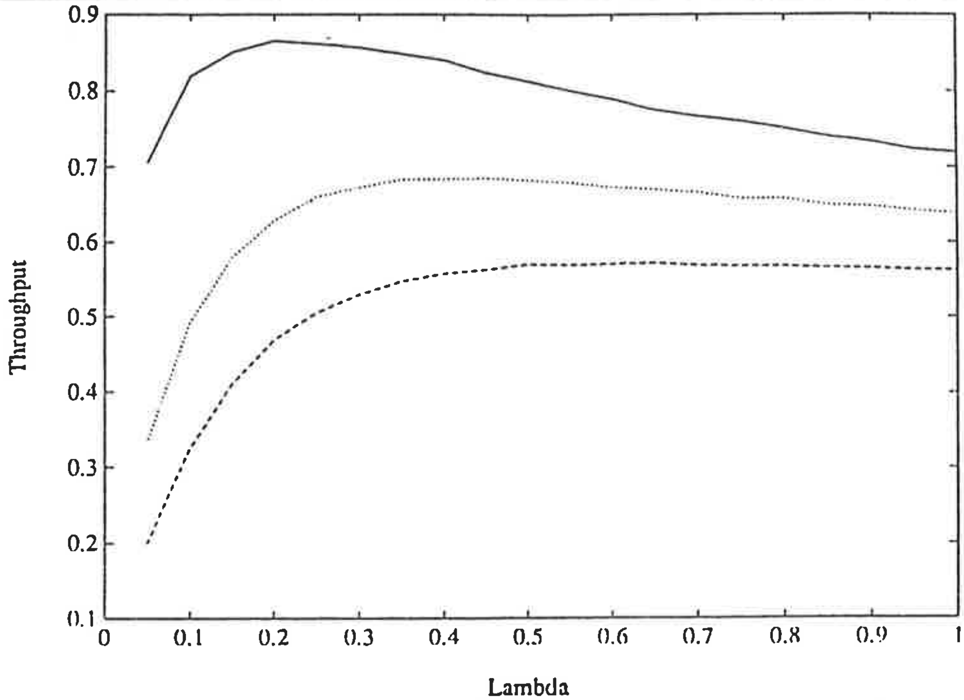



Figure 5 Throughput, 10 Mobile Nodes, L=2, p=7

Overhead Length= 0.2 (solid), 1.0 (dot), 2.0 (dash)

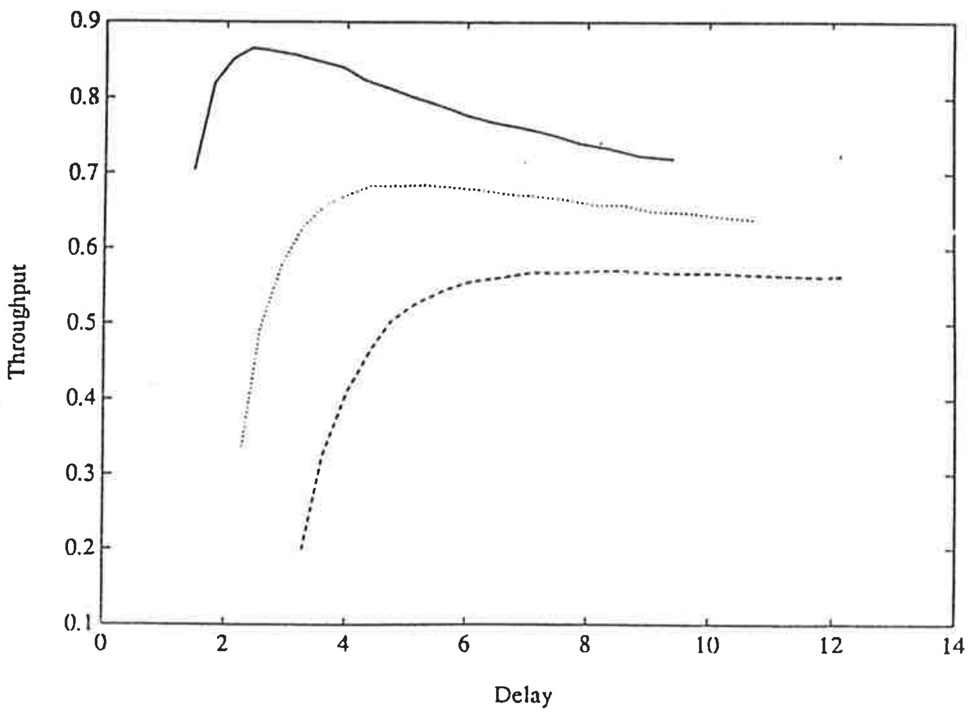



Figure 6 Delay-Throughput, 10 Mobile Nodes, L=2, p=7

Overhead Length= 0.2 (solid), 1.0 (dot), 2.0 (dash)

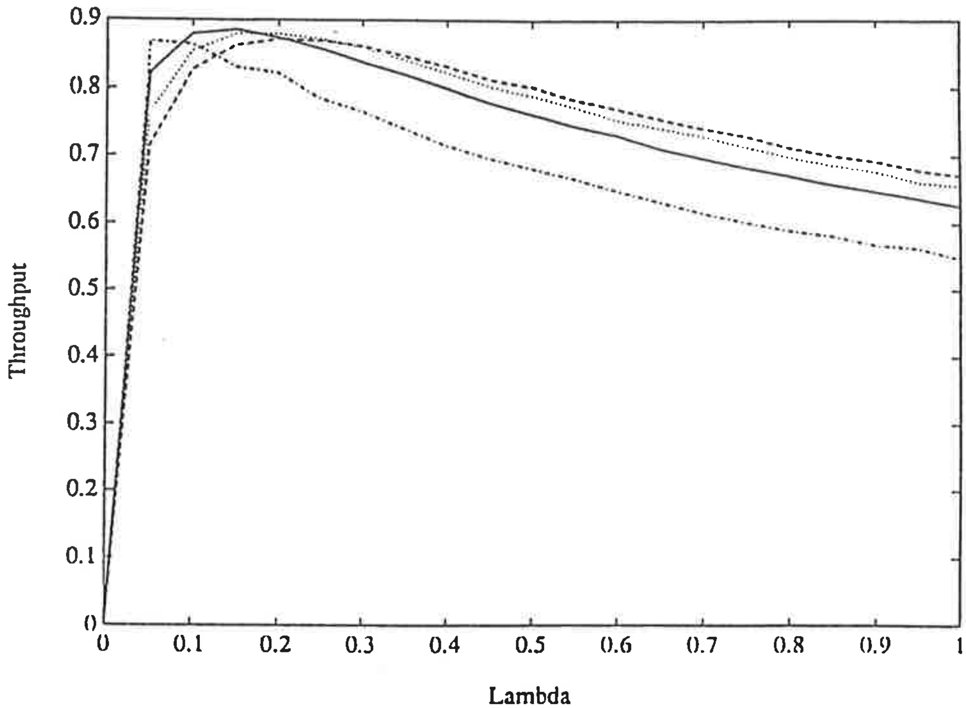



Figure 7 Throughput, 10 Mobile Nodes, p=5, L=1,2,3,4

Overhead Length=0.05, 0.1, 0.15, 0.2 (dash-dot, solid, dot, dash)

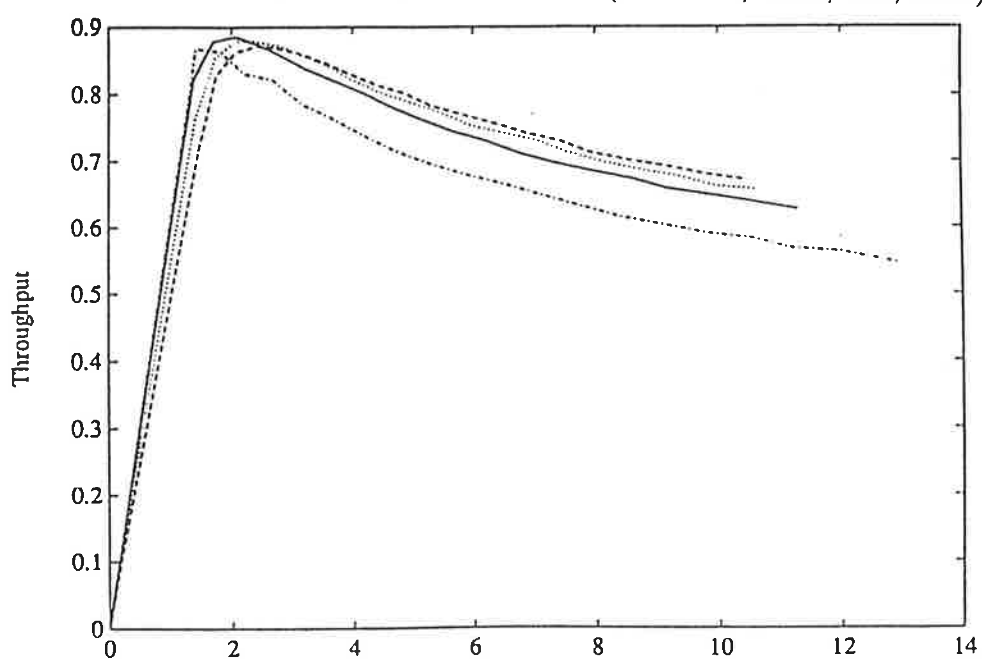



Figure 8 Delay-Throughput, Same Parameters as Figure 7

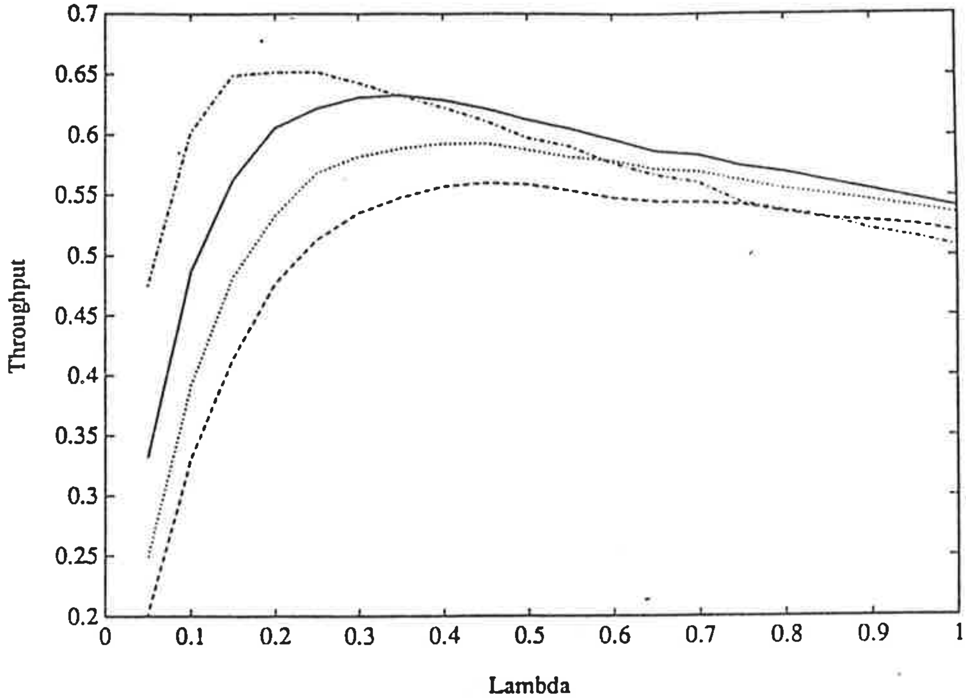



Figure 9 Throughput, 10 Mobile Nodes, p=5, L=1,2,3,4

Overhead Length=0.5, 1.0, 1.5, 2.0 (dash-dot, solid, dot, dash)

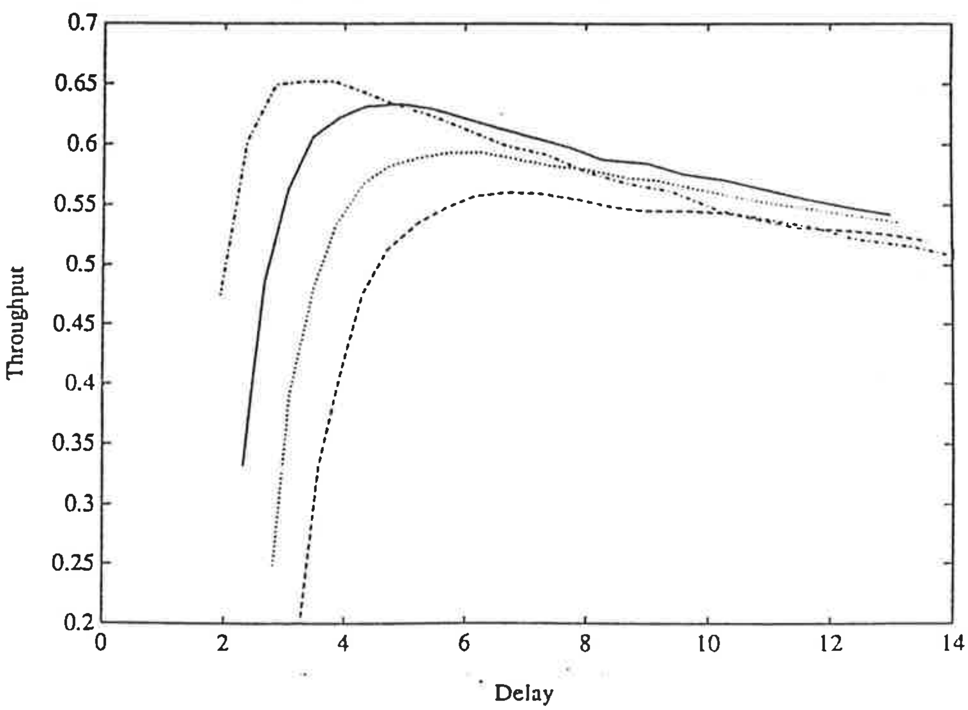
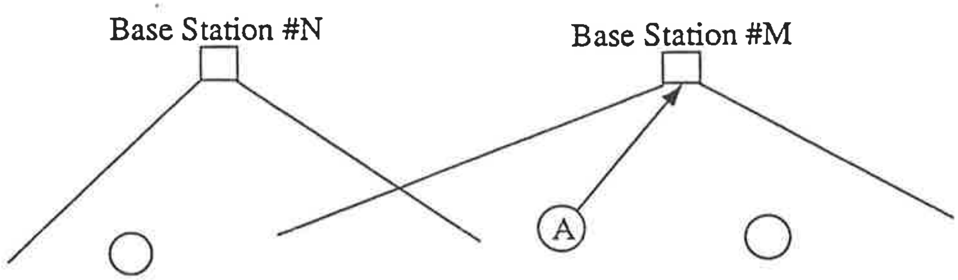
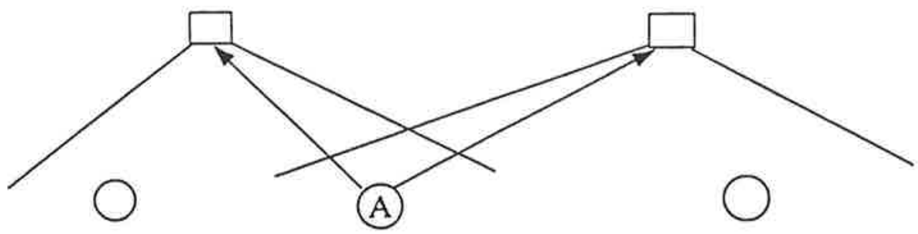


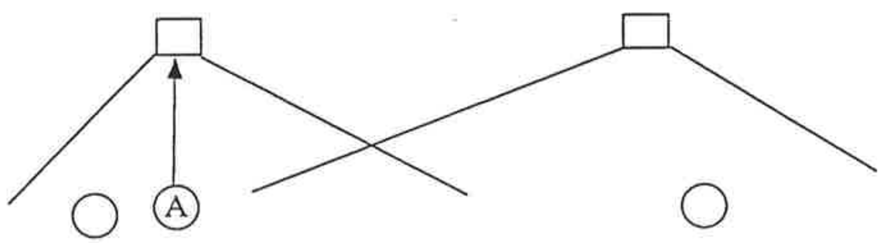

Figure 10 Delay-Throughput, Same Parameters as Figure 9




Active Mobile Node Sending Packet to Base Station #M

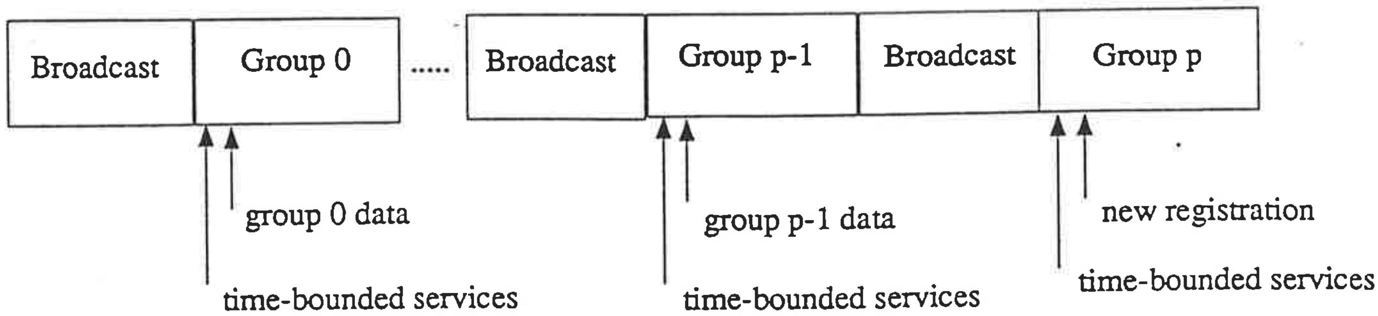



Active Mobile Node Sending Packet to Base Station #M or #N in the Joint Cell

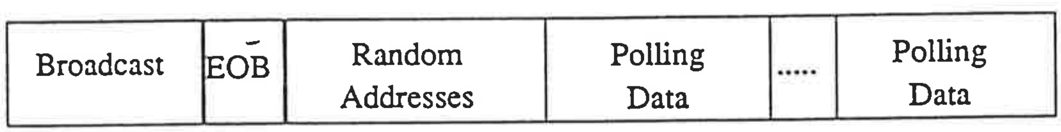



Active Mobile Node Sending Packet to Base Station #N

Figure 11 RAP with No Handoff




Super-Frame Structure




Frame Structure

Figure 12 Frame Structure of GRAP