中華民國八十六年全國計算機會議

無線網路媒體存取控制架構

A Highly Flexible Multiple Access Protocol for Wireless Networks

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摘要

媒體存取控制是決定系統效率的一個主要因素，本文提出一個架構在有限投射平角上的碰撞法則並提供效益評估。

Abstract

Due to the limited bandwidth of wireless communications systems, an efficient medium access control protocol is essential to meet the growing demand of wireless access. Most multiple access protocols require contentions (collisions) in the process of acquiring the communication medium. While collisions cannot be avoided, successive collisions that consist of the same active stations are totally unnecessary. Successive collisions not only waste bandwidth but also raise the concern of saturation in the channel. In this paper, we take a different approach (protocol *FMAC*) to solve the problem of repetitive contentions involving the same set of stations. Protocol *FMAC* is based on the theory of finite projective planes. By using the property of single point intersection for an arbitrary pair of sets, we can minimize the number of unnecessary collisions. Protocol *FMAC* is highly flexible, and has many features including adaptation in an heterogeneous environment, support for priority assignment and handoffs in wireless networks, and extension of ATM services to mobile users. A performance evaluation shows that the throughput of the system is higher than that of slotted ALOHA. By dynamically adjusting the retransmission probability, protocol *FMAC* is stable.

Index: Multiple Access. Wireless Networks,

1. Introduction

A multiple access protocol that dynamically allocates the spectrum to a large number of mobile users must be efficient and flexible. In general, multiple access schemes can be classified as follows: static assignment, random access, and demand assignment[14,15]. The static protocols such as frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA) are not suitable for sporadic and bursty data traffic since the subchannel (time slot) assigned to a particular station could be underutilized. Random access protocols, such as ALOHA, slotted ALOHA[1], CSMA[14], have a relative low throughput. In addition, these protocols are unstable which means that the channel can get saturated due to the accumulation effect of unsuccessful transmission attempts. The polling scheme (demand assignment), e.g., the randomly addressed polling (RAP)[4,5], manages the multiple access in a distributed fashion. Polling is appropriate when the number of stations is small, and the propagation delay is short. Other demand assignment protocols such as the R-ALOHA[13], PRMA[7,8], Reservation Random Access[10] and Tree protocol[3] apply a decentralized control over random access.

In general, multiple access protocols require that an interested station competes randomly using slotted-ALOHA like scheme either at the reservation stage (e.g., R-ALOHA) or at the channel acquiring stage (e.g., slotted ALOHA). If a collision occurs, the station simply delays for a random amount of time. It is likely that the same group of stations will collide consecutively. The potential disadvantage of consecutive collisions of the same group of stations is that the throughput of the channel is reduced and the mean delay is increased. In this paper, we propose a new contention scheme (protocol *FMAC*) to avoid successive collisions involving the same group of stations. The contention mechanism is based on the theory of finite projective planes. A finite projective plane of N points consists of N sets of points, each of which has $m+1$ points, where $m^2+m+1=N$ [2,11]. For example, a finite projective plane of 7 points has the following 7 sets of points: (1, 2, 3), (1, 4, 5), (1, 6, 7), (2, 4, 6), (2, 5, 7), (3, 4, 7), and (3, 5, 6). If each active station is assigned a set of points, and only transmits at the time slots corresponding to the point numbers of its set, any pair of active stations will compete exactly once in a time frame of N time slots. There are some differences between the *FMAC* and slotted ALOHA. First, a station in slotted ALOHA can transmit as it wishes when a packet is generated,. In *FMAC*, a station with a packet to send has to wait for its turn (eligible time slot), and then transmits with a probability p, where $0 \le p \le 1$. If a collision occurs, or the current eligible time slot is empty, it transmits with a probability q in the next eligible slot, where $p \le q \le 1$. Second, the selection of a time slot for retransmission in *FMAC* is based on finite projective planes as proposed in this paper, rather than being a random delay.

The stability of protocol *FMAC* is achieved by dynamically self-adjusting the retransmission probability, as is different from the algorithms used to adjust the retransmission probability in slotted ALOHA [6,9,12,16] Protocol *FMAC* is highly flexible, and supports a variety of features needed in wireless systems including handoffs, priority, heterogeneity, and integration of voice and data. Since the carrier sense capability is not required for each active station, the hidden terminal problem is not an issue for *FMAC*.

2. Protocol *FMAC*: Finite Projective Plane Based Multiple Access Mechanism

The problem with the current contention schemes is that same competing stations for an available time slot may collide over and over, and thus reduces the throughput and lengthens the delay. Take binary exponential backoff in CSMA/CD as an example. The probability of the first successive collision is 0.5 for two stations, and approaches 1 when the number of stations involved increases. It may not be possible to avoid collisions completely, but eliminating collisions which involve identical competing stations certainly is worthy of the effort. Consequently, a contention scheme has to satisfy the following two requirements. First, an active station is allowed to compete until it reserves a time slot successfully. Second, each time an active station participates in a competition, it should compete with a completely different group of active stations. However, it is allowed to compete with the same set of stations after a few time slots have gone by, since the competing stations may have successfully transmitted their packets. Most protocols, including the protocols mentioned in Section 1, can meet the first requirement easily, but fail to meet the second requirement. We found that the contention mechanism based on the theory of finite projective planes satisfies both requirements.

2.1 Finite Projective Planes

A finite projective plane consists of sets of points [1]. Two distinctive sets intersect at exactly one point. A finite projective plane of order m has $m+1$ points on each set, and $m+1$ sets contain each point. As a result, both the total number of points (N) and the total number of sets (N) on the plane are equal to m^2+m+1. For instance, a finite projective plane of order two, has seven points and seven sets on the plane as shown in Section 1. As an illustration, the sets for a finite projective plane of 13 points (order 3) and 21 points (order 4) are listed as follows.

13 points: (1,2,3,4), (1,5,6,7), (1,8,9,10), (1,11,12,13), (2,5,8,11), (2,6,9,12), (2,7,10,13), (3,5,10,12), (3,6,8,13), (3,7,9,11), (4,5,9,13), (4,6,10,11), (4,7,8,12). **21 points:** (1,2,3,4,5), (1,6,7,8,9), (1,10,11,12,13), (1,14,15,16,17), (1,18,19,20,21), (2, 6, 10, 14, 18), (2, 7, 11, 15, 19), (2, 8, 12, 16, 20), (2, 9, 13, 17, 21), (3, 6, 11, 16, 21), (3, 7, 10, 17, 20), (3, 8, 13, 14, 19), (3, 9, 12, 15, 18), (4, 6, 12, 17, 19), (4, 7, 13, 16, 18), (4, 8, 10, 15, 21), (4, 9, 11, 14, 20), (5, 6, 13, 15, 20), (5, 7, 12, 14, 21), (5, 8, 11, 17, 18), (5, 9, 10, 16, 19).

2.2 Mapping of Protocol *FMAC*

To apply the theory of finite projective planes to contention mechanism, we first choose a finite plane of N points, where N is equal to the number of stations. Second, each station is assigned a set of the finite projective plane. Since there are totally N sets, each station is assigned a distinctive set. Third, a station only transmits at the time slots corresponding to the point numbers of the set assigned to that station. The following example shows the contention scheme for 13 stations. In the example, the station numbers range from 0 to 12, and the time slot numbers start at 1. Assume that the stations that have packets to send include: 0, 4, 5, 6, 7, 11, and 12. Figure 1 shows the configuration of time slot assignment.

Note that there are three possible outcomes for each time slot: empty, collision, and successful transmission. If there is only one transmission station, the station transmits successfully. If more than one stations are involved, a collision occurs, and frames are destroyed (capture effect is not considered). As shown in Table 1, in 13 time slots, 7 stations transmit successfully, and the throughput is about 54 percent.

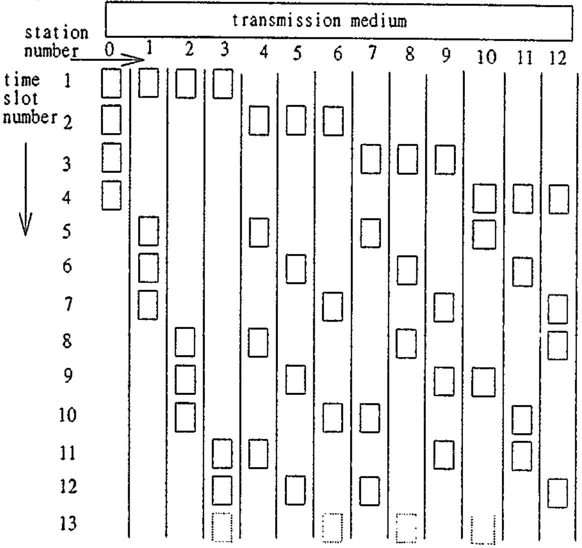

Figure 1: The Configuration of Time Slot Assignment for 13 Stations

Table 1: The Stations That Transmit in the Time Slots of a Frame

Time Slot No.	0	1	2	3	4	5	6	7	8
Transmission Stations	0	4, 5, 6	7	11 ,12	4	5, 11	6, 12	12	5

Time Slot No.	9	10	11	12
Transmission Stations	11	Empty	Empty	6

2.3 Descriptions of the Protocol

The protocol works as follows. The stations, including both virtual stations and active stations, are numbered 0 through N-1. A virtual station, defined as a station that never transmits a packet is used to avoid overcrowding of transmission attempts. At each time slot, each active station has a probability p to transmit a packet for the time slot. In other words, each active station may compete for a time slot with a probability p at each of the time slots corresponding to the point numbers of the set assigned to that station. These time slots are called eligible time slots for that station. If a collision occurs, it will delay until next eligible time slot when the active station is allowed to compete (retransmission) for an available time slot. By then it can transmit with a probability q (retransmission probability), where $p \leq q \leq 1$. Consequently, each retransmission station has a probability q that is greater than or equal to p, to transmit a packet in each of its eligible time slots after an initial collision or bypass. Now the question is: what is the appropriate value of q? If q is too small (almost equals p), an active station may have little chance to retransmit, especially in an environment that have many stations, and each active station has a very small probability (p) to generate a packet in a time slot. As a result, it is forced to hold back its packet. If q is chosen to be 1, the protocol may become unstable due to the accumulation of unsuccessful transmission attempts. We summarize the protocol as follows.

1. A station that wishes to transmit can do so in the time slots it is eligible to transmit. Assume that a station has a probability p to generate a packet in a time slot
2. Each station needs to keep track of the current time slot number, and may become active at any time slot.
3. The time slot number wraps around when it reaches the end of the time frame.
4. For the first collision or bypass, the active station will retransmit in the next time slot to which it is eligible with a retransmission probability(q) that equals 1. For each subsequent collision or bypass, the retransmission probability is reduced according to one of the following two policies.

Policy A: Uniform reduction of retransmission probability

$$q_{i+1} = 1 - \Delta, \quad \text{where } \Delta = \frac{1-p}{m-1}$$

The retransmission probability begins with 1, and is reduced by a constant amount Δ for each subsequent eligible time slot, until it reaches p.

Policy B: Exponential reduction of retransmission probability

$$q_{i+1} = q_i - \frac{q_i - p}{2} = \frac{p + q_i}{2}$$

The retransmission probability is reduced by the amount that equals half the difference between the previous retransmission probability and p. For example, station 0 is eligible to transmit at time slots 1, 5, 9, 13, and 17. At time slot 1, station 0 is allowed to transmit. If a collision happens, it skips time slots 2, 3, and 4, and transmits with a probability 1 at time slot 5. If there is a collision at time slot 5, the retransmission probability is reduced to 0.75, assuming that p equals 0.5. If a collision happens again at time slot 5, the retransmission probability is reduced to 0.625. The process continues and the retransmission probability will eventually converge to p.

The first retransmission adjustment policy takes an uniform step approach. The retransmission probability decreases at a constant pace, until it equals p after m eligible time slots The second one is a fast start approach. The retransmission probability reduces fast during the initial eligible time slots, and then gradually slows down its pace.

2.4 Priority Implementation

Protocol *FMAC* can implement priority scheme which gives some stations higher probability to obtain a time slot than others. The priority option is required as the networks go into multimedia, where some traffic type has a higher priority than others. The proposed contention scheme can easily be adapted to priority assignment. The high priority station is assigned more than one set of points. If a station is assigned K sets of points, then it is allowed to transmit at the time slot numbers corresponding to the point numbers of the K sets assigned to that station. The probability of a successful transmission for that station is approximately increased by K times.

It is also possible to guarantee a time slot in a frame by using virtual stations. We first define the orthogonal sets of points of finite projective plane of N points as follows. The point numbers of an orthogonal set k are the set numbers that contain a point number k. For instance, the 7 sets of points: $s_1 = (1, 2, 3)$, $s_2 = (1, 4, 5)$, $s_3 = (1, 6, 7)$, $s_4 = (2, 4, 6)$, $s_5 = (2, 5, 7)$, $s_6 = (3, 4, 7)$, and $s_7 = (3, 5, 6)$ constitute a finite projective plane of S of 7 points. The orthogonal sets of the finite projective plane S^* is obtained as follows. The point numbers of s_i^* are the set numbers of S, that contain the point number i. As an example, the point numbers of s_1^* include the set numbers of S that contain point number 1. The orthogonal sets of S are identical to the sets of S, i.e., $s_i^* = s_i$ in this example. Physically, the point numbers of an orthogonal set s_i^* indicate the stations competing at time slot i. If we want to make sure that a station i is guaranteed a time slot in a time frame, we simply choose an orthogonal set that contains i, and then let all stations but i be virtual stations. For instance, $s_1^* = (1, 2, 3)$, station 1 is guaranteed to secure time slot 1, if stations 2, and 3, are virtual stations. By choosing virtual stations carefully, a station can be assured of a time slot.

2.5 Heterogeneous Environment

Some stations may have higher probability of transmitting packets than others. If we still treat them the same, and assign each station a set of points, the optimal throughput may not be achieved. Protocol *FMAC* can be used in a heterogeneous environment where stations may have different probabilities in using the medium. Or, in some cases, the stations may have different packet sizes, which entail a variety of time slot sizes. Of course, we may choose a large time slot that can fit the largest packet size. But it may waste the bandwidth for many other stations with small packets to send. Here, an heterogeneous environment can mean variations in packet sizes, or the probabilities in transmitting a packet among active stations. Protocol *FMAC* can accommodate both situations easily. We describe them as follows.

2.5.1 Variations in Probabilities

For example, there are 19 station, one of which has a probability of 0.6 to issue a packet in a time slot, and each of the other 18 stations has a probability 0.2 to issue a packet. The size of the finite projective plane 21 is appropriate. Each station is assigned a set, and two sets are unused. All stations are treated the same regardless of variations in probability. The throughput of the channel is about 0.4096.

Alternatively, we may combine three stations , each of which has probability 0.2, into one. In other words, a set of point numbers is shared by three stations, thus we only need 7 sets. Since each set has three point numbers (time slots), each station is assigned one slot. As shown in Figure 2, the number in the circle indicates the time slot number that the station is allowed to compete. The station with a probability 0.6 is eligible to compete at time slot numbers 3, 5, and 6. Through the merging technique, the channel efficiency has been increased to 0.5248.

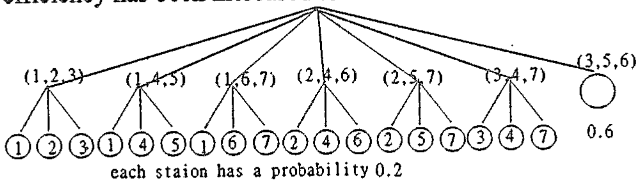

Figure 2: Sharing of a Set of Points in a Heterogeneous Environment

2.5.2 Variations in Packet Sizes

If the packet sizes of active stations are different, the throughput of the transmission channel can be further increased by compacting multiple packets in one time slot. The idea works by allowing stations, which have small packet sizes to share one time slot. For example, the packet sizes of competing stations are *L, L,2L,..., 2L*, we would allow the first two stations, say, *A*, and *B*, to share one set of points. In the time slots that stations *A* and *B* are eligible to compete, station *A* transmits at the first half of the time slot, and station *B* transmits at the second half of the time slot. Note that in this example, the packet size 2*L* is equal to the data rate of the channel multiplied by the duration of a time slot.

2.6 Time Bounded Services

Sometimes, it is imperative for an active station obtain a time slot within a time bound. The guarantee of a time slot is achieved through the manipulation of time slot assignment. Consider the same example in Section 2.1, but only stations numbered 4 through 8 are active stations, and the rest are virtual stations. No matter how many stations are active, each station is guaranteed a time slot in the frame.

Lemma: For a finite projective plane of N points, it is possible to provide time-bounded service to at least $2m$ - 1 stations.

<Proof> A finite projective plane of N points has N sets, which can be further divided into a number of group. A group is defined as the sets that contain a fixed point, and the total N sets can be divided into m+1 groups. Each set in group 1 contains point number 1, and each set in group 2 contains point number 2, etc. Except for group 1, each group has m sets. These groups (2 through m+1) are called candidate groups for providing time-bounded services.

To select sets for time bounded services, we arbitrarily choose two groups (2 m sets) from the candidate groups, and randomly remove one set from these two groups (2 m - 1 set left). For example, in the finite projective plane of 13 points, the sets in each group are as follows. Group 1:(1,2,3,4), (1,5,6,7), (1,8,9,10), (1,11,12,13), group 2:(2,5,8,11), (2,6,9,12), (2,7,10,13); group 3 : (3,5,10,12), (3,6,8,13), (3,7,9,11); group 4: (4,5,9,13), (4,6,10,11), (4,7,8,12). Here, we may select the sets of groups 2 and 3, and discard one set, say, (3, 7, 9, 11). The resulting configuration of competition is shown in Figure 3.

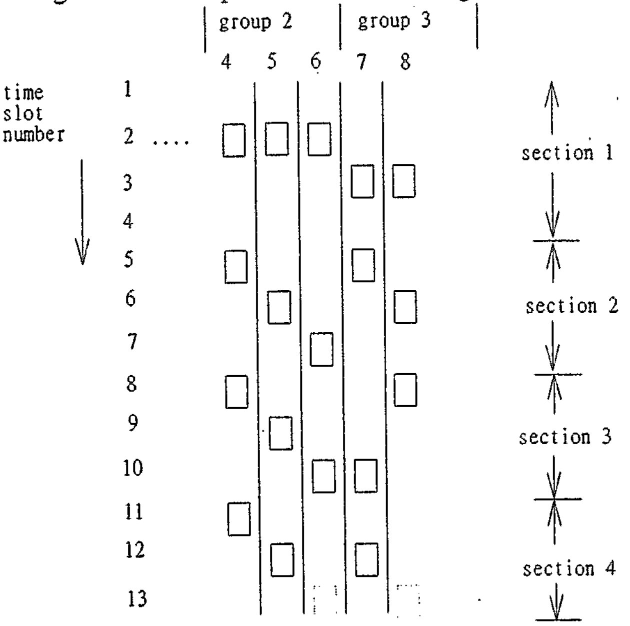

Figure 3: The Configuration of Time Bounded Service

We also divide the time slots in the frame into sections. Similar to grouping, the first section has four time slots, and each of the rest sections has three time slot. Totally, there are m sections, and m^2+m+1 time slots. We can show that each active station can obtain a time slot in a time bound of m^2+1 time slots. There are at most two competing station in each time slot starting with the second section, and there is exactly one time slot in each section with one competing station. The station that transmits successfully will "trigger" another station in the next section, and so on. As a result, the number of stations that transmit successfully grows exponentially, from 1, 2, 4, ..., etc. It takes m-1 sections to let all active stations ($2m$ -1) finish. Adding the number of time slots in the first section, the number of time slots needed for the time bounded service is m^2+1.

By choosing an appropriate value of N, the tightest time bound of a station can be achieved. Each of the stations is allocated a time slot within the time bound of m^2+1 time slots. Suppose the tightest time bound among all active stations is TB time slots.

The inequality has to be satisfied, $m^2+1 \le TB$. As a result, the size of the finite projective plane N should be less than $TB + \sqrt{TB-1}$, and the number of stations of time bounded service time is $2\sqrt{TB-1}$ -1.

2.7 The Demand Assignment Approach

Protocol *FMAC* can also be modified for demand assignment with distributed control, where the allocations of time slots are based on reservations. Time slot assignments are determined during the reservation stage using either contention method or pre-allocated method. For the contention method, all active stations compete for the reservation mini time slots as if they were competing for regular time slots. In the pre-allocated method, each active station is allowed to reserve a time slot in the pre-assigned mini time slot. Protocol *FMAC* can be used as the contention scheme for reservation of mini time slots. We describe the approach as follows. In each reservation stage, protocol *FMAC* is used in competing for the mini time slot. The station that reserves a mini time slot successfully has the right to transmit in the time slot number corresponding to the mini time slot number. It is possible that some of the mini time slots are not reserved successfully either because of collisions or no station is reserving. In that case, the time slots corresponding to the unreserved mini time slots are given the second chance for competing. Only the stations that are eligible to compete in the corresponding mini time slot can compete.

3. Performance Evaluation

Protocol *FMAC* increases the chance of successful transmissions by eliminating successive collisions of identical stations. To determine the throughput and the mean delay of the contention mechanism, we first describe the model as follows.

1. We adopt the finite projective plane of N points, which has m^2+m+1 sets, and each set has $m+1$ points. In other words, it allows up to N stations (active + virtual stations) in the system. The value of N is chosen such that the probability that there is only one station competing at a time slot is maximized. As a result, N is a function of both the number of active stations and the probability that an active station has a packet to transmit.
2. The number of active stations is R, and the number of virtual stations is $N-R$.
3. Each active station has a probability p to request the communication channel, that is, to transmit a packet at a time slot. If a collision occurs, the active station will wait until next eligible time slot when it is allowed to compete, and transmits with a probability q. For the performance evaluation in this section, we assume q is equal to p. If q is 1, the channel may not be stable. In the next section, we will show how to dynamically adjust the retransmission probability to achieve stability.
4. The message sent by all active stations are of fixed length and is equal to the duration of the time slot multiplied by the channel rate.

3.1 The throughput

The throughput (T) is the probability that there is only one station competing at

a time slot. The number of active stations in each time slot is $R/(m+1)$, thus,

$$T=\binom{\frac{R}{m+1}}{1}p(1-p)^{\frac{R}{m+1}-1}$$

When $pR/(m+1)$ equals 1, T is maximized, and equals $(1-p)^{\frac{1}{p}-1}$, as shown in Figure 3 below.

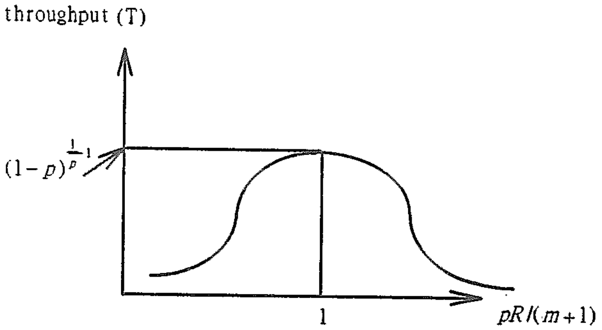

Figure 3: The Throughput (T) as a Function of $pR/(m+1)$

Table 2 shows the maximum throughput that can be achieved. And N is the sum of the number of virtual stations and the number of active stations, and m^2+m+1 is greater than or equal to R. Note that the maximum throughput (T) is independent of the number of active stations.

Table 2: The Maximum Values of the Throughput (T) for Various Values of p

p	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
T	0.38	0.40	0.43	0.46	0.5	0.54	0.59	0.66	0.77

In general, N is chosen such that the following two conditions need to be met.

$$\frac{pR}{m+1}=1$$

$$m^2+m+1 \geq R$$

The latter is needed to ensure that the number of sets of the finite projective planes is greater than or equal to the number of active stations. We use the following three examples to illustrate the concept.

Example 1: $R=6$, $p=0.5$

To get the maximum throughput, by the first condition, we get $m=2$. The second condition is also satisfied since there are 7 sets of the finite projective plane. Thus, there is one virtual station, and the throughput of the protocol is equal to 0.5.

Example 2: $R=20$, $p=0.1$

By the first condition, $m=1$, the size of the finite projective plane that makes the maximum throughput is 3.

Apparently, the second condition cannot be satisfied.

In this case, we may choose m equals 4, and the throughput T is less than the optimal value.

When an active station transmits a packet at a time slot, and a collision occurs, it will try to transmit in the next eligible time slot with a probability q that equals p. Note that the retransmission probability must equal p; otherwise, the retransmission attempts pile up, and the channel is saturated which can reduce the throughput, and increase the mean delay.

3.2 Mean Delay

The mean delay (D) is calculated as follows.

Each station has a probability of $\frac{(1-p)^{\frac{1}{p}-1} N}{(m+1)R}$ to secure the channel in the time slot it is eligible to compete. When the station misses one slot, it has to wait on the average m time slots before next attempt. As a result, the mean delay is calculated as follows.

$$D=\sum_{i=0}^{\infty} miS(1-S)^{i-1} \text{ where } S=\frac{(1-p)^{\frac{1}{p}-1} N}{(m+1)R}$$

Make a substitution and we get the mean delay as follows.

$$D=\frac{m(m+1)R}{(1-p)^{\frac{1}{p}-1} N} \cong \frac{R}{(1-p)^{\frac{1}{p}-1}}$$

The mean delay D, varies with both the size of the finite projective planes N, and the probability p, that a station may issue a packet in a time slot.

4.Stability Analysis.

5. Further Remarks

6. Conclusion

Omitted to save space

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