國立交通大學

資訊學院　資訊學程

碩士論文

具壅塞控制能力之低延遲分散式分時多工無線隨意網路存取協定

A Low-delay Distributed TDMA Protocol with Congestion Control for Wireless Ad Hoc Networks

研 究 生：林福龍

指導教授：簡榮宏 教授

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國立交通大學　資訊學院　資訊學程碩士班

摘要

在無線通訊技術中，減少訊息傳輸延遲是一項重要的議題。特別是對於傳輸延遲敏感度高的應用更是格外重要。因此，近來許多智慧型運輸系統（Intelligent Transportation System, ITS）的安全應用，對於傳輸延遲也有著嚴格的要求。 現有的無線網路媒體存取控制(Medium Access Control, MAC）協定，大致上可分成：競爭模式（Contention-based）及排程模式（Schedule-based）兩大類。然而競爭模式的MAC隨機存取機制，在網路密集度很高的時候，常會產生嚴重的爭用情形。另一方面，排程模式採取的是有限的延遲（bounded-delay）存取機制，其透過將時間分割以及排程藉以達到無競爭傳輸。在密集的網絡中，node 數量可能會超過每一frame 原先所規劃的 slot 數量，導致有 node 無法取得屬於自己的傳輸slot，因而無法進行訊息傳送。雖然使用較大的frame size 將允許更多 nodes 無競爭傳輸，但每一個 node 須花費較長的時間來等待下一次傳送週期，而產生較大的傳輸延遲。

在本文中，我們致力於結合排程模式 MAC 與功率控制技術，以避免通道擁塞，並同時保持較低的傳輸延遲。

關鍵字：車載隨意網路(Vehicular ad hoc networks)，分散式分時多工(distributed TDMA)，功率控制(power control)　。

A Low-delay Distributed TDMA Protocol with Congestion Control for Wireless Ad Hoc Networks

Student: Fu-Lung Lin Advisors: Dr. Rong-Hong Jan

Degree Program of Computer Science
National Chiao Tung University

ABSTRACT

Reducing transmission delay is an important issue in wireless communications. It is particular critical to delay-sensitive applications. Many recent safety applications in Intelligent Transportation System (ITS) also have strict requirements on the delay.

Existing Media Access Control (MAC) protocols for wireless networks typically fall into two categories: *Contention-based* and *Schedule-based* MACs. However, due to the random access nature, contention-based MAC may incur severe contention, especially in high density networks. Otherwise, schedule-based MAC achieves bounded-delay access by dividing time into frames and let each frame contain several slots for collision-free transmissions. However, in a dense network, the number of nodes could exceed the frame size such that some node may not be able to reserve a free slot for its transmission. A larger frame size will allow more nodes to reserve a free slot for their transmissions, but it may also incur a larger delay since each node has to wait for a longer period of time before the next frame coming.

In this paper, we aim to combine schedule-based MAC with an adaptive power control technique to avoid channel congestion and at same time to retain a lower end-to-end delivery delay.

Keywords: Vehicular ad hoc networks, distributed TDMA, power control.

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林福龍
僅誌於交通大學
計算機網路實驗室

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Chapter 1

Introduction

Reducing transmission delay is an important issue in wireless communications. It is particular critical to delay-sensitive applications, such as Cooperative Collision Avoidance (CCA) in vehicular networks [1] in which the front vehicle provide earlier warning to the backward vehicles by forwarding emergent messages hop-by-hop in order to avoid the chain-car collision. Providing a low-delay or even delay-bound protocol can significantly improve the road safety. Many recent safety applications in Intelligent Transportation System (ITS) also have strict requirements on the delay.

Existing Media Access Control (MAC) protocols for wireless networks typically fall into two categories: *Contention-based* and *Schedule-based* MACs [2]. The contention-based MAC allows network nodes to randomly access the same radio channel without pre-coordination among the nodes. Any colliding node goes through a random binary back off time before the next contention, e.g. the CSMA/CA mechanism in IEEE 802.11 and WAVE/DSRC MACs[3]. A contention-based MAC has better channel reusability if the contention among nodes is below certain level [4]. However, due to the random access nature, it may incur severe contention, especially in high density networks. Besides, strategies like RTS/CTS are usually used to avoid hidden terminal nodes in contention-based protocols, which however, is not applicable to broadcast transmission that has a vital role in Vehicular Ad Hoc Networks (VANETs). Although numerous contention-based protocols were designed to mitigate the access delay in probabilistic senses [1, 5, 6], they cannot guarantee a bounded access delay in extreme environments.

Schedule-based MAC is a kind of Time Division Multiple Access (TDMA) that offers an inherent collision-free scheme by assigning unique time slots for every node to send or receive data. For instance, the MAC protocols in [7, 8], [9-*13*] achieve bounded-delay access by dividing time into frames and let each frame contain several slots for collision-free transmissions. Moreover, the hidden terminal problem can be implicitly resolved if the slots were allocated according to two-hop information among nodes [9]. It means that a reliable broadcasting at MAC-layer can be easily achieved in a schedule-based protocol.

However, in a dense network, the number of nodes could exceed the frame size (i.e. number of slots in each frame) such that some node may not be able to reserve a free slot for its transmission. It is the so called *congestion problem* [14]. Furthermore, if too many nodes cannot obtain slots, the whole network could be partitioned or even disconnected. This problem is particularly important in vehicular environments where vehicles density may concentrate at some areas, e.g. toll station, and at picking hours, and the messages loss due to the lack of a free slot could incur a deadly car accident.

A number of researches have devoted to resolve the congestion problem by adjusting the frame size according to node density [12]. A larger frame size allows more nodes to reserve a free slot for their transmissions, i.e. a larger capacity, but it may also incur a larger delay since each node has to wait for a longer period of time before the next frame coming. The impact could be more significant to the end-to-end transmission, where packets will be relayed through multiple hops the destination, incurring a larger end-to-end delay. Contrarily, a smaller frame size has a lower delay, but some nodes may not be able to reserve a free slot when all slots in a frame were reserved, i.e. channel congestion occurs. So, there is a tradeoff between channel congestion and transmission delay problems.

In this paper, we aim to combine schedule-based MAC with an adaptive power control technique to avoid channel congestion and at same time to retain a lower end-to-end delivery delay. More specifically, by reducing the transmission range of nodes, the proposed protocol tries to maintain a smaller frame size, which is sufficient for all nodes to make a successful slot reservation, in order to reduce the waiting time at each relay node. Moreover, our protocol guarantees the network connectivity even if transmission range of some nodes were reduced. Experimental results show that our protocol decreases at most 28% in delay.

In the rest of the paper is organized as follows: In Section 2, we give an overview of schedule based MACs and introduce related works. Existing power control mechanisms for channel congestion problem are also discussed. In Section 3, we introduce a well-known schedule-based MAC protocol and discuss how power control technique avoids channel congestion problem. Then, our MAC protocol is presented in Section 4. In Section 5, we evaluate the performance of our protocol through a series of simulations. Finally, conclusions are given in Section 6.

Chapter 2

Related Works

Reservation ALOHA (R-ALOHA) [15] is a well-known distributed TDMA protocol. It divides channel access time into slots and allows each node contending to reserve an available slot and using the slot in subsequent frames as long as the node has packets to send. However, R-ALOHA has a potential risk of collision problem if hidden nodes exist.

Borgonovo *et al.* [13] proposed an improved protocol, called Reliable R-ALOHA (RR-ALOHA), to overcome the hidden terminal problem. In RR-ALOHA, when a node enters the network, it listens to the slots occupation for an entire frame, and broadcasts a Frame Information (FI) on an un-used slot to reserve a own slot. Then, the node listens to the FI from its one-hop neighbors for one complete frame to get the slot occupation information within the range of its two hops, and can successfully reserve the slot if there is no other node reserving the same slot. Later, the authors incorporated the RR-ALOHA with an optimal multi-hop broadcast service and parallel transmissions [9]. The protocol, called ADHOC-MAC, uses a small number of relaying terminals to cover all nodes in the network so as to eliminate the broadcast retransmissions.

The authors in [12] proposed an adaptive MAC protocol for wireless vehicular network base on ADHOC MAC, called Adaptive ADHOC (A-ADHOC). The protocol implements a mechanism supporting an adaptive frame length. Every node tries to send out a specific message to double (or halve) the frame length, when the number of nodes is more than an upper threshold (or less than the lower threshold). In other words, the congestion problem can be resolved by adaptively changing the frame length at each node. However, the relaying time could be prolonged at some node having a longer frame length, which in turn, cause a larger end-to-end delivery delay.

A number of studies have suggested integrating dynamic TDMA for vehicular networks [8, 10, 11]. Federal Communication Consort (FCC) allocates 75MHz bandwidth at 5.9GHz spectrum for Wireless Access Vehicle Environments (WAVE)[3]. The bandwidth is divided into seven channels, including a control channel (CCH) and six service channel (SCHs). IEEE 802.11p/1609 further divides the channel access time into a CCH interval and a SCH interval for multi-channel operations. Nodes can content for the control channel to exchange control or emergent messages on control channel at CCH interval, and transmit non-safety messages on service channels at SCH interval. Although WAVE is specifically defined for efficient message disseminations in VANETs, research evidences showed that its contention-based nature may lead to a severe collision especially on the control channel.

Lu et al. proposed a dedicated multi-channel MAC (DMMAC) with adaptive broadcasting [11]. It further divides the CCH into an Adaptive Broadcast Frame (ABF) and a Contention-based Reservation Period (CRP). In the duration of ABF, each node tries to content the free slot for receiving or sending the FI frames based on RR-ALOHA. Similar to A-ADHOC, DMMAC can dynamically increase the number of time slots in ABF, called ABF Length (ABFL), when CCH is congested. However, it may also cause a larger end-to-end delay if the ABFL is longer.

The VeMAC [8] further divides the CCH into several time slots and assigns disjoint sets of time slots to vehicles moving in opposite directions and to Road Side Units (RSUs). It can avoid *merging collision* that happens when two vehicles are approaching to each other and transmitting packets using the same slot [16]. The authors showed that for the same number of contending nodes and available time slots, nodes can acquire slots on the CCH more efficiently.

Ning Lu et al. [10] propose a MAC protocol similar to RR-ALOHA, called the Distributed Reliable Multi-channel MAC (DR-MMAC). They showed that packet delivery ratio of the IEEE 802.11p MAC drop drastically when the number of vehicles is greater than 10, because of the contention in control channel and hidden terminal problem. DR-MMAC can guarantee 100% delivery ratio. But the results also indicate that the delivery ratio could decrease if too many vehicles join the network, since the number of nodes may exceeds the frame size.

The VeSOMAC [7] is a location-aware schedule-based MAC for VANETs. It achieves delay reduction by temporally order the slots according to the sequence of vehicles entering on the road. In this way, messages can be quickly forwarded to the front or rear vehicles within the same frame if slots were properly ordered, providing better vehicle safety.

A number of contention-based MAC protocols [4, 5, 17, 18, 19, 20] were designed to avoid congestion, i.e. traffic load on the wireless channel, by controlling the transmission power. Torrent-Moreno *et al*. [4] proposed Fair Power Adjustment for Vehicular environments (FPAV) algorithm. The main idea is to reserve a chunk of bandwidth for event driven message so that communication of safety applications is not hindered by channel saturation. But, it needs central entity presence at all locations. In further study [18], the same authors proposed a “distributed” algorithm in which each collects status information and exchanges power level to overcome the drawbacks of FPAV. However, it suffers from a huge overhead when relaying information. Mittag et. al [19] improve the overhead in Distributed Fair Power Adjustment for Vehicular networks (D-FPAV) by exchanging the number of vehicles in each road segment and use the information to estimate the load. [21] Through maintaining a low connectivity in a dense network (e.g., only communicate with the closest neighbors) for reducing packet collisions. The above protocol can mitigate channel congestion and delay by power control, but it still can not guarantee a lower or even bounded access delay.

To the best of our knowledge, there was no schedule-based MAC protocol resolving the congestion problem and at the same time achieving a lower delay. Our research is based on the perspectives: Combining schedule-based MAC with a power control mechanism to overcome the two challenges.

Chapter 3

Preliminaries

This chapter first introduces the RR-ALOHA protocol. Next, we discuss what would happen if the channel is congested. Then, we introduce the main idea of our protocol and discuss the challenges when designing the protocol.

3.1 Basic Operation of RR-ALOHA

Suppose that there are N slots in one frame, and there are M nodes trying to contend for their slots. Each node shares the slot occupation information from its one-hop neighbors to each other. When a node enters the network, it listens to the slots occupation for an entire frame, and broadcasts a FI on an un-used slot to reserve the slot. Then, the node listens to the FI from its one-hop neighbors for one complete frame. If all FIs from its one-hop neighbors received by node i in last frame are marked as "Slot j is BUSY by node i", this contending is successful and node i will use the slot j in subsequent frames as long as the node has packets to send. Otherwise, node i needs to re-contend in next frame, because some nodes of its one-hop neighbors did not receive the FI of node i.

As shown in Figure 1, the frame size is 6. Nodes D, F and G are one-hop neighbors and form a fully connected network. Similarly, nodes A, B and D as well as node A, C and E are two groups of one-hop neighbors. If node A wants to join the network, it listens to the FIs from its one-hop neighbors, i.e. nodes B, C, D and E. After listening to the FIs, node A knows that slots 1, 2, 4 and 5 are used, respectively, by nodes B, C, D and E, and it can get the slot occupation information of its two-hop neighbors (i.e., slot 3 is used by node F and slot 5 is used by node G) from node D. As a result, node A will find that slot 6 is free. When slot 6 comes, node A transmits its FI at slot 6. When successfully transmitted the FI packet, node A waits six slots. If all FIs from its one-hop neighbors (i.e., nodes B, C, D and E) indicates that slot 6 was marked as BUSY by node A, slot 6 is successfully reserved and will be used for the subsequent transmissions by node A.

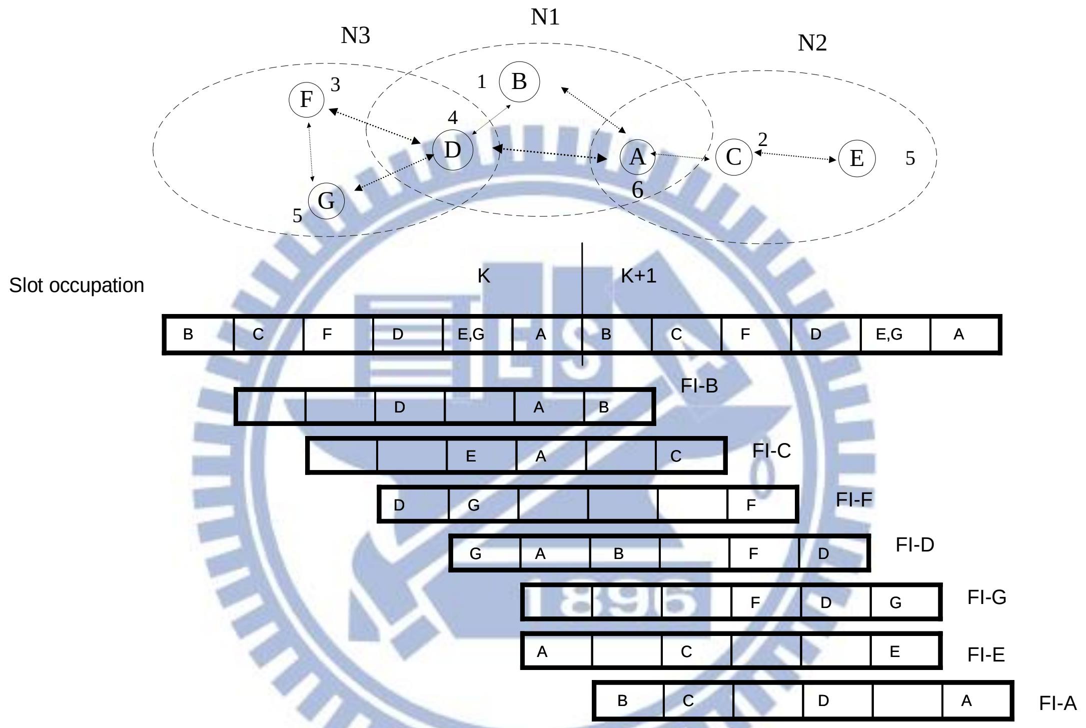


Figure 1. An example of slot reservation with frame size 6.

3.2 Slot Congestion Problem

The above process goes well if all nodes can reserve their slots. But, what would happen when the channel (slot) congestion in a dense network? (i.e., $N < M$). As shown in Figure 2, there are 7 nodes contending for 5 slots. Assume that nodes B, C, D, E, F and G have reserved slots 1, 2, 4, 5, 3 and 5, respectively. At this time, node A cannot transmit its FI since there is no more free slot (i.e., after node A listened to the FIs from its one-hop neighbors, node A finds that all slots were reserved). In this case, node A has neither the right to transmit nor the guarantee of receiving packet from all its neighbors. In other words, node A does not join to the network.

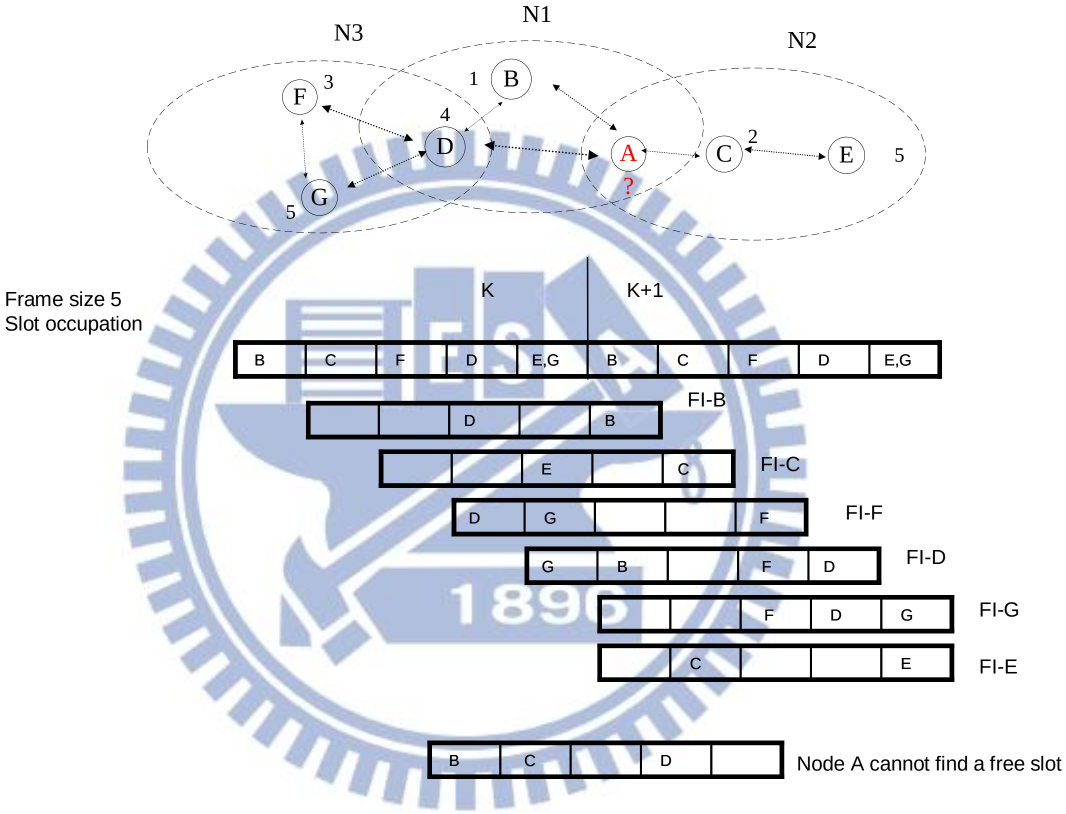


Figure 2. A scenario where slots are congested.

Even worse, the network could be partitioned if some critical node did not join the network. As shown in Figure 3, node A is the only node bridging networks N1 and N2, and it cannot forward any packet from node C or node E to nodes B and D, because it did acquire a free slot. Similarly, any packet from node B or node D cannot be forwarded to nodes C and E via node A for the same reason.

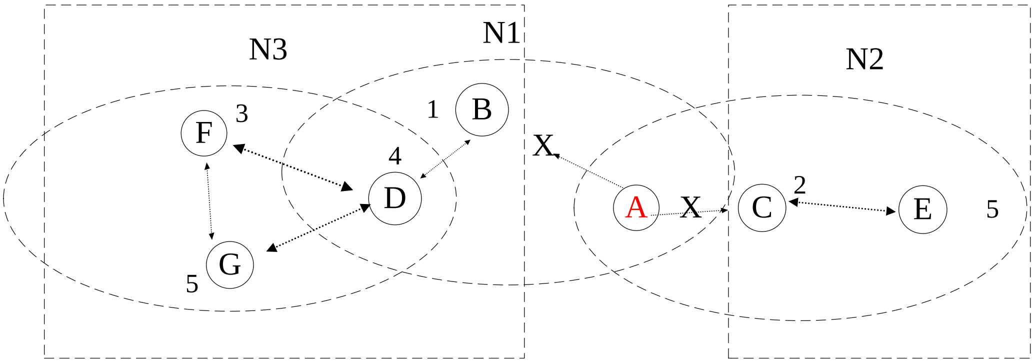


Figure 3. A scenario of network partition due to the lack of a free slot.

3.3 How Power Adjustment Diminishes Slot Congestion

The basic idea to resolve the channel (slot) congestion problem is by adjusting the transmission power. As shown in Figure 4, by shrinking the transmission power of node A so that is covers only nodes B and C (without covering node D), slot 3 is free to node A. Thus, node A can transmit its FI on slot 3 if there is no other node reserving the same slot for an entire frame. In this way, we can avoid that nodes A and F use the same slot to send their FIs, which in turn, incurs a collision at node D.

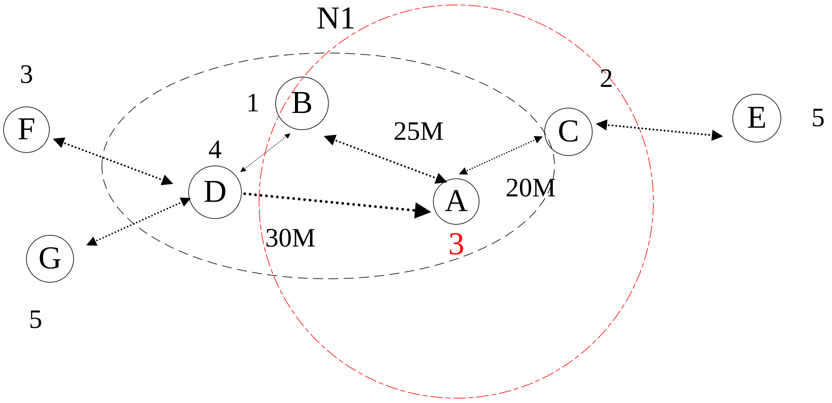


Figure 4. Node A adjusting its transmission power to achieve a slot

3.4 Challenges

From the above example, we can see that reducing the transmission power can improve the spatial re-use in the network and resolve slot congestion. However, how to determine the transmission power for congested nodes? Such as the case in Figure 5, the default power is 35 meters. Suppose that node A adjusts its transmission power from 35 to 34 meters, the slot congestion problem still exists, since the power range remains too large to infer with other nodes. On the other hand, if node A reduces its transmission range to 24 meters, the transmission range is too smaller. As shown in Figure 6, it may cause a larger end-to-end delivery delay. When node A broadcast a message, node F receives the message four hop counts later (i.e., A -> C -> B -> D -> F). But, the best path should be A -> B -> D -> F. Even worse, node A will disconnect to other nodes if node A adjusts its transmission range below 20 meters as shown in Figure 7. After adjusting power levels it must create unidirectional links (i.e., a lower power node might not be received at a higher power node). Such as that node A can receive FI from nodes B, D, but nodes B, D cannot receive FI from node A as shown in Figure 6. These are the significant challenges what need to overcome.

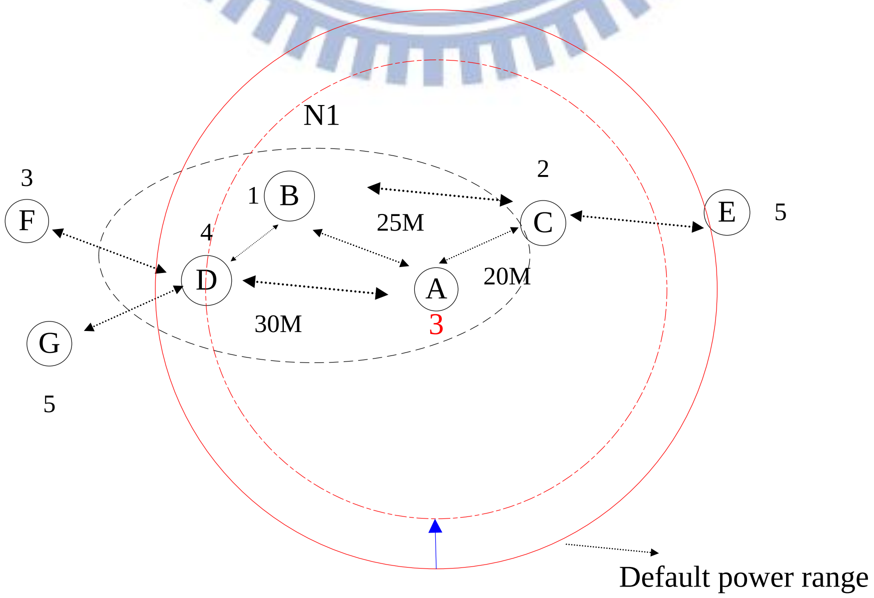


Figure 5. The power level is too larger.

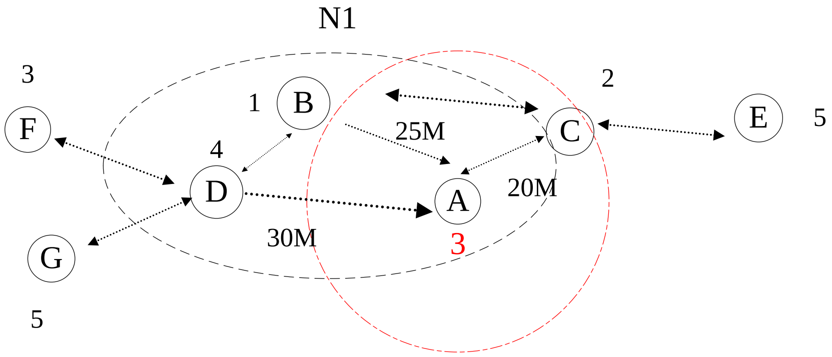


Figure 6. The power level is too smaller.

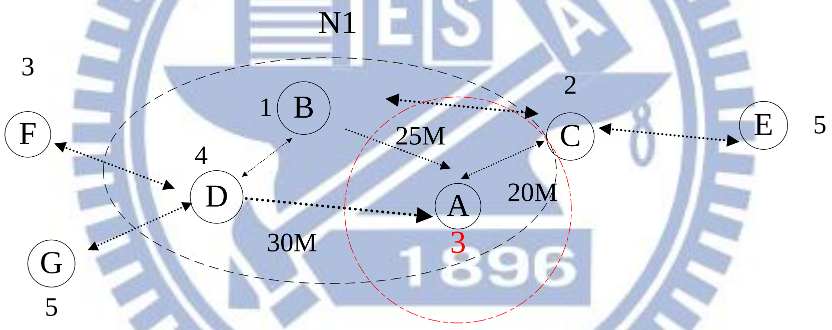


Figure 7. The power level is too smaller and node A disconnect to other nodes.

Chapter 4

Protocol Design

In this chapter, we present the Power-Control ALOHA (PC ALOHA). First, we describe the main idea that how we control the power. Then, we define a unique data structure, called Extended Frame Information (EFI) in our protocol. After that, an adaptive power control mechanism is presented. We also discuss how we handle the symmetric and connectivity problem in our protocol. The algorithm of PC-ALOHA is summarized in the last part.

4.1 Main idea

In the Chapter 3, we have observed that a node can reserve a reserved slot if reducing the power so that a receiving node will not be interfered by the two nodes and the most challenging problem is to determine the transmission power for the congestion nodes.

Our goal is to reduce the power for congested nodes with the least increment to the frame size, i.e. the least increment to the end-to-end delay. The main idea is explained as follows: As a node is congested, we intend to reduce the least amount of the node’s transom power such that any transmission from the node will not interfere to any neighboring node at a certain slot. At the same time, we avoid the network be partitioned to different groups. As shown in Figure 8, it is sufficient to obtain a free slot 3 if the congestion node A only reduces the power to cover nodes B and C. Why we select to re-use slot 3, because there aren’t any one-hop neighbors use the slot 3. In this way, it has the least reduction of power, which avoids the possibility of increasing end-to-end delay when node A wants to broadcast a message to its neighbors.

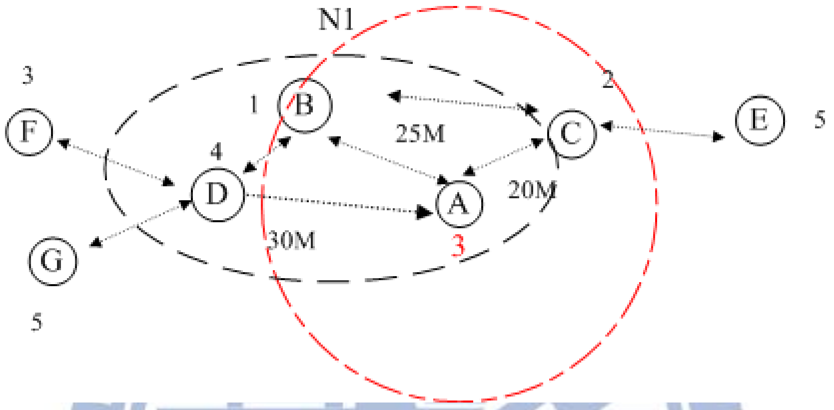


Figure 8. Adjust the congestion node A power levels.

4.2 Extended Frame Information

To discover the possible spatial reusability according to the positions additionally carried in the FI, called extended FI (EFI). The content of FI is shown in Figure 9. ID indicates the identifier of the node that sends this FI. Length indicates the FI packet length. X, Y, Z indicates the X, Y, Z coordinate system information from Global Positioning System (GPS). Slot Information (SI) contains the status (FREE or BUSY) of the corresponding slot.

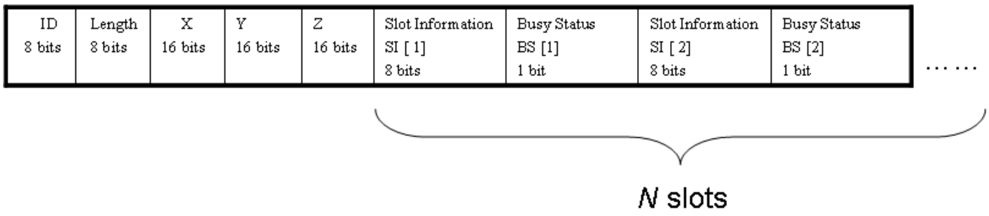


Figure 9. Information recorded in EFI.

Each node will maintain an EFI table includes the slot status, distance to the one-hop node, and which node is using the slot as shown in Table 1. We establish a definition as:

Definition: *A slot can be recorded as "FREE", "BUSY by node i" or "RESERVED by node i" by node j:*

1. *"**BUSY by node i**": When node j receives the FI from node i, and the information will be written into its broadcasting EFI.*
2. *"**RESERVED by node i**": The information come from its one-hop neighbors. It means that a two-hop neighbor has occupied this slot, so node j cannot contend for this slot or collisions may happen somewhere. And Node j won't write this record into its broadcasting EFI.*
3. *"**FREE**": The slot is free. Node j can contend for this slot.*

slot	1	2	3	4	5
id	B	C		D	E
status	BUSY	BUSY	FREE	BUSY	RESERVED
distance	25m	20m		30m	20

Table 1. EFI table.

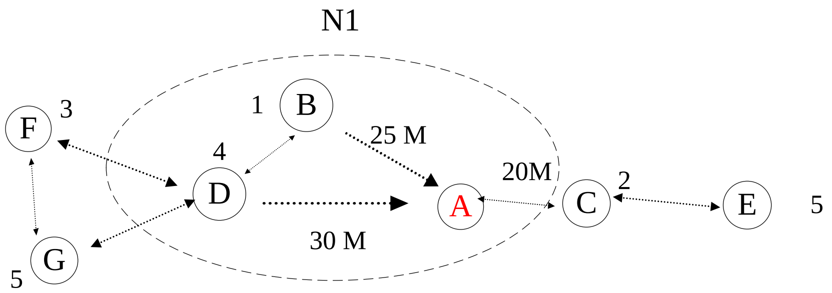
4.3 Adaptive Power Control

Before we present how reservation works, we should present some definitions as shown in Table 2.

V_i	：the node i
D_{ij}	：Distance from node *i* to node *j*
OH	：One-hop member
TH	：Two-hop member
S_{OH}	：Slot using by one-hop member
S_{TH}	：Slot using by twp-hop member
P_{ε}	：The minimum amount of power range decrease
P_{adj}^{t}	：The transmission power range after adjusting
$P_{\max}^{t}$	：The node maximum transmission power range
D_{ji}^{r}	：The distance from the transmission node *j* to received node *i*

Table 2. Symbol table.

The node V_i join the network, if V_i can find a FREE slot from ($S_{OH} \cup S_{TH}$), send the EFI on the FREE slot. Otherwise, when the channel is congestion (i.e., V_i cannot find any more FREE slot from EFI table, we can choice a S_{TH} slot that can make its own EFI table as FREE through shrinking the transmission radius as $P_{adj}^{t} = D_{ij} - P_{\varepsilon}$. Now, V_i can contend for the FREE slot. After adjusting power range, it will create unidirectional links. The V_i must maintain the EFI table carefully. When V_i receives an EFI from V_j, V_i must take care about the D_{ji}^{r} between two nodes. If V_i finds $P_{adj}^{t} < D_{ji}^{r}$, V_i still need mark S_{OH} as BUSY. But, V_i must mark S_{TH} as FREE. However, two different *OHs* maybe share the same S_{TH} information at same time, we just record the Min{ D_{ji}^{r}, D_{ki}^{r} } in the EFI table. Where Min{ D_{ji}^{r}, D_{ki}^{r} } is the shortest transmission range between them.



slot	1	2	3	4	5
id	B	C	F	D	E, G
status	BUSY	BUSY	RESERVE	BUSY	RESERVE
distance	25m	20m	dist to D 30m	30m	dist to C 20=min{20, 30}

Figure 10. channel congestion at node A

As shown in Figure 10, the frame size is 5. Node A receives the EFI from its one hop members (i.e., B, C and D) and maintains its own EFI table. Node A cannot transmit its EFI since there is no more free slot. Before node A adjusts its transmission power, node A selects a RESERVED slot 3 (or 5) to send its EFI with maximum transmission power 35 meters, node A will incur a collision at D (or C).

As shown in Figure 11 and Table 2, the slot 3 is only used by two-hop member (i.e., node F). After node A adjusts power range to 30 - P_{ε} meters, node A can mark the slot 3 as FREE as shown in Table 2 and then node A can send its EFI at slot 3 without colliding at node D. At same time, node A still marks slot 4 as “slot 4 BUSY by node D”.

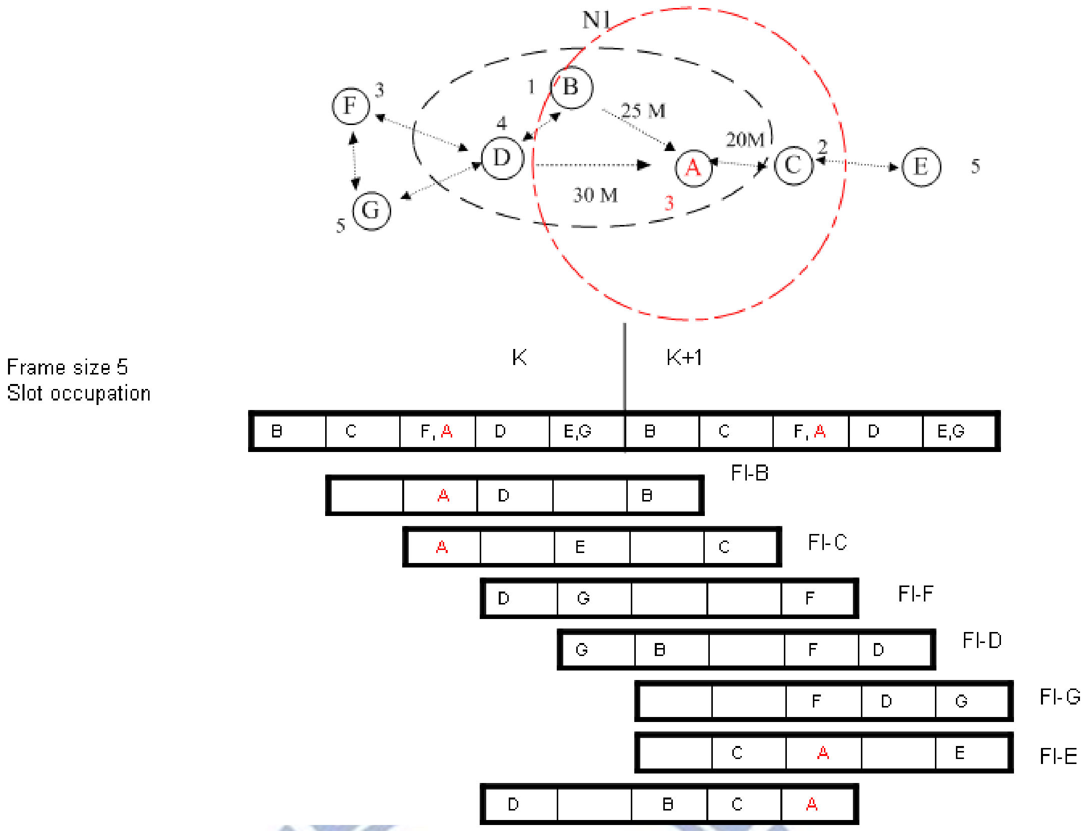


Figure 11. Controlling power for channel congestion at node A

slot	1	2	3	4	5
id	B	C		D	E, G
status	BUSY	BUSY	FREE	BUSY	RESERVE
distance	25m	20m		30m	dist to C 20=min{20, 30}

Table 3. Controlling power for channel congestion at node A

4.4 How to maintain network Connectivity

The *Gabriel Graph (GG)* is a connection scheme proposed by Gabriel and Sokal (1969) [22], two points are connected when the circle associated with the diameter that has the two points as endpoints does not have another point within its circumference. Mathematically, the GG is defined as follows: An edge (u,v) exists between vertices u and v if no other vertex w is present within the circle whose diameter is $\overline{uv}$. In equational form : $\forall w \neq u, v:\ d_{uv}^2 < d_{uw}^2 + d_{vw}^2$. As shown in Figure 12, points *u* and *v* are Gabriel neighbors. Otherwise, the presence of point *w* within the circle prevents points *u* and *v* from being Gabriel neighbors as shown in Figure 13.

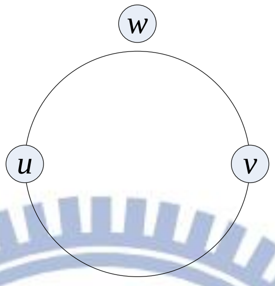


Figure 12. Points *u* and *v* are Gabriel neighbors.

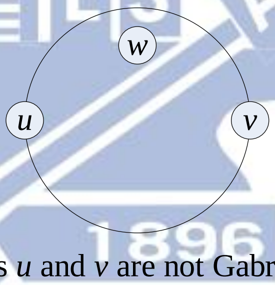


Figure 13. Points *u* and *v* are not Gabriel neighbors.

From the definition of GG, we can try to adjust the transmission power of the dumb node(s) (i.e., a node cannot reserve any free slot.), if we can find a node *w* as shown in in Figure 13 from the one hop neighbors. At this time, the dumb node(s) can re-use the time slot(s) and maintain network connectivity at same time. The significant difference between Figure 16 and Figure 17 is that we can guarantee the network still connectivity when frame size is 5. For our application, the algorithm should be run in a distributed fashion by each node in the network, where a node needs information only about the positions of its one-hop member(s) as the algorithm's input.

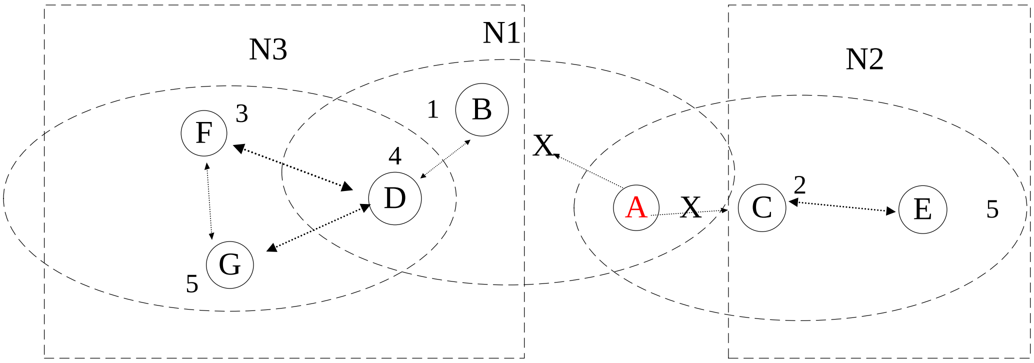


Figure 14. Network topology of RR-ALOHA MAC protocol

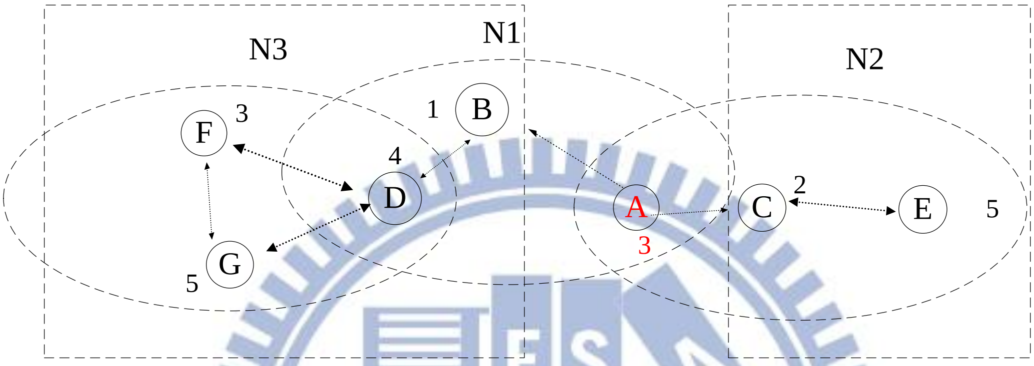


Figure 15. Network topology of PC-ALOHA MAC protocol

4.5 How to handle in symmetricity

Adjusting transmission range will create unidirectional links (i.e., node C can receive EFI from nodes node A, but nodes A cannot receive EFI from node C) as shown in Figure 16. When the new join node A try to reserve slot 5 for sending the EFI and the power range can cover to C, because it cannot get any slot status from C's EFI(i.e., A cannot know E exist.). At this time, both nodes A and E would transmit their EFI at slot 5 that incur a collision at C (i.e., C's EFI will mark the slot 5 as FREE, because it cannot receive any EFI at slot 4 in last frame). Then, E will find one EFI of its one-hop neighbor(s) don't mark slot 5 as "BUSY by node E". Now, node E will detect that incur a collision at somewhere. Node E just need to re-entrance the network and it won't cause any chain reaction.

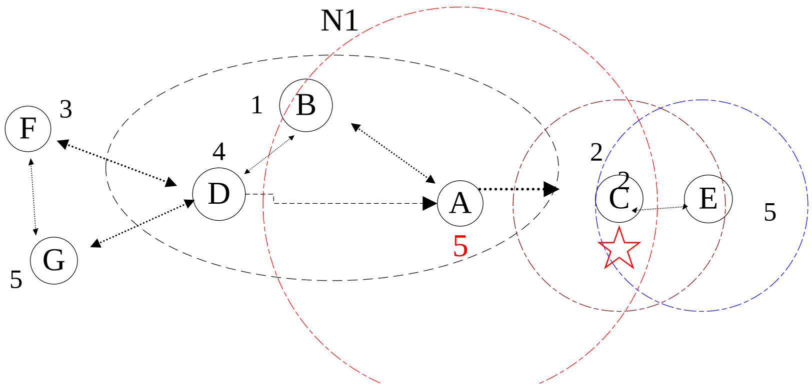


Figure 16. Network symmetricity

4.6 PC-ALOHA Protocol

We summarize the above describe into a series of protocols the main operation of PC-ALOHA at each slot when node join the network, operation of EFI sending and receiving routine, and Power Control of congestion node in Figure 17~20. And the PC-ALOHA flow chart has shown in Figure 21.

```
Protocol 1:   Operation of PC-ALOHA at each slot timer Protocol:
/* parameters and Flag defined
   WAITING         : waiting to contend for a slot
   CONTENDING : occupation or contending for a slot
   Status                    : status of the node
*/
      if  node is waiting to contend for a slot then
            if the coming slot is free then
                  if I try to contend it then
                        send the EFI. call sendFI ()
                        set Status=CONTENDING of the node
                  else
```

```
                  reset Timer of the node
                  set Status=CONTENING of node
          for ( i = 0; i < TOTAL_SLOT; i ++)
              check the free slot
          if no more free slot then
              select transmission power. call SelectPowerRange( )
              Timer of system++
              return
    else if    my contending slot is coming then
          if there isn’t any collision (feedback from receive algorithm) then
              send the EFI call. call sendFI()
              set Status=CONTENDING of the node
              return
          else // Collision
              Set Status=CONTENDING of node and contend for slot again.
              reset Timer of the node
              Timer of system++
              return
    else
          Timer of system++
          receive EFI and maintain EFI table only
          return
```

Figure 17. Operation of PC-ALOHA at each slot timer Protocol

```
--------------
Protocol 2    Operation of EFI sending routine:
--------------
/*
Parameters and Flag defined
*/
    if my contending slot is coming then
        send the EFI packet by transmission power piggybacking my X, Y,
        and Z coordinate and slot using status of my one-hop neighbors
        return
```

Figure 18. Operation of EFI sending routine Protocol.

```
--------------
Protocol 3 Operations at the reception of an EFI
--------------
/*
Parameters and Flag defined
*/
if my transmission power >= distance to the transmission node then
maintain slot status, distance to the transmission node and who
use the slot in its EFI table
else
    mark the slot that only using by two-hop neighbors as FREE
return
```

Figure 19. Operations at the reception of an EFI Protocol

```
--------------
Protocol 4 Power Control of congestion node
--------------
/*
Parameters and Flag defined
*/

for (i=0; i < TOTAL_SLOT; i ++)
    if the slot used by two hop node only then
        for (j=0; j < TOTAL_SLOT; j ++)
            check each one-hop neighbor
            if we can find one-hop node didn't satisfy GG constraint then
                set release flag =TRUE
            else
                continue
    else
        continue
if the release flag ==TRUE then
    adjust my transmission power
    break
```

Figure 20. Power Control of congestion node Protocol.

The details of protocol 1 are described as follows:

- line 1: Check if the node is waiting to contend for slot, after listening to the slots occupation for an entire frame
- line 2~5: If the incoming slot is free and the node try to contend for the free slot. First, the node must send out an EFI packet and change the node status.
- line 6~8: If the node don’t contend for the incoming free slot, it would wait the next free slot coming and repeat line 2~5 steps.
- line 9~14: If the node cannot find any free slot, the node can follow the GG constraint to shrink its transmission power for re-using the reserved slot.
- line 15~24: Check whether all the one-hop neighbors received my EFI. If agree, sends out the EFI packet at the coming slot again. Otherwise, try to wait another free slot coming and contend for it.
- line 25~28: Just listening the EFI packets from one-hop neighbors and maintaining EFI table.

The details of protocol 2 are described as follows:

- line 1~4: Nodes share their perceived information and X, Y, Z coordinate to each other by properly broadcasting packet EFI.

The details of protocol 3 are described as follows:

- line 1~3: If our power range can cover to the transmission nodes, we will record all EFI information from one-hop neighbors in EFI table.
- line 4~6: We must consider unidirectional links. When our power range cannot cover to the transmission nodes, we can mark the slot which using by two-hop neighbor only as FREE.

The Power Control of congestion nodes are described as follows:

- line 1~2: Find out the slot only used by two-hop neighbor from our EFI table
- line 3~6: Find out a one-hop node which didn't satisfy GG constraint when we adjust the power range. Then, we can guarantee the network still connectivity.
- line 7~8: Go to next step.
- line 9~10: Go to next step.
- line 11~13: If we can find out the one-hop neighbor, shrink our transmission power

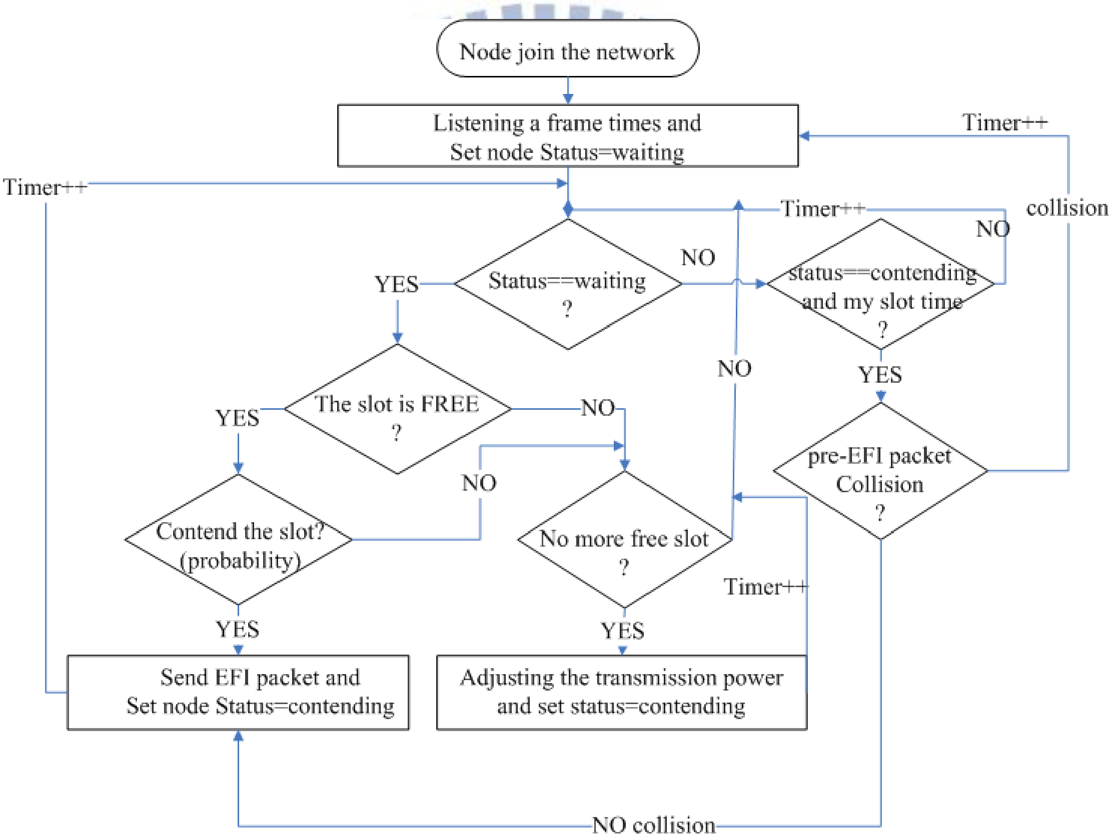


Figure 21. PC-ALOHA flow chart

As shown in Figure 2, there are 7 nodes contending for 5 slots. After a listen interval, each node has to contend to reserve an available slot and use the slot in subsequent frames. According to our protocol and flow chart, the simulation statuses of each node shown in Figure 22 and described as follows:

-- In Frame 1:

Node B: Try to send an EFI to contend **slot 1** for its transmission, and set up the status from WAITING to CONTENDING at same time.

Node C: Try to send an EFI to contend **slot 2** for its transmission, and set up the status from WAITING to CONTENDING at same time.

Node F: Try to send an EFI to contend **slot 3** for its transmission, and set up the status from WAITING to CONTENDING at same time.

Node D, G: Try to send an EFI to contend **slot 4** for its transmission, and set up the status from WAITING to CONTENDING at same time. Actually, the EFIs will collision at node F. In next frame (i.e., frame 2), EFI from its one-hop neighbor, Node F, does not indicate that slot 4 was marked as BUSY by node D or G.

Node A, E: Try to send an EFI to contend **slot 5** for its transmission, and set up the status from WAITING to CONTENDING at same time. The EFI will collision at node C. So, node A and E need to listen a frame interval and contend a free slot for its transmission again.

-- In frame 2:

Node B, C and F:

The contending is successful and nodes B, C and F will use the **slot 1, slot 2 and slot 3** in subsequent frames as long as the node has packets to send.

Node A, D, E and G:

The contending is unsuccessful. Nodes A, D, E and G have to listen a frame time and try to reserve a free slot again. All of them must set up the status from CONTENDING to WAITING at same time.

-- In frame 3:

Node A: It does not contend a free slot for its transmission in frame 3.

Node D: Send an EFI to contend other **slot 4** for its transmission, and set up the status from WAITING to CONTENDING.

Node E, G: Try to wait another free **slot 5** coming and contend for it. And set up the status from WAITING to CONTENDING. Nodes E and G are not two-hop neighbor, so they will reserve slot 5 for their transmission successfully.

-- In frame 4:

Node A: Node A can not find any free slot for its transmission end of frame 3. According to our power control protocol shown in Figure 21, it will find slot 3 can be re-used. All of Node A~G will reserve a slot for their transmission in subsequent frames

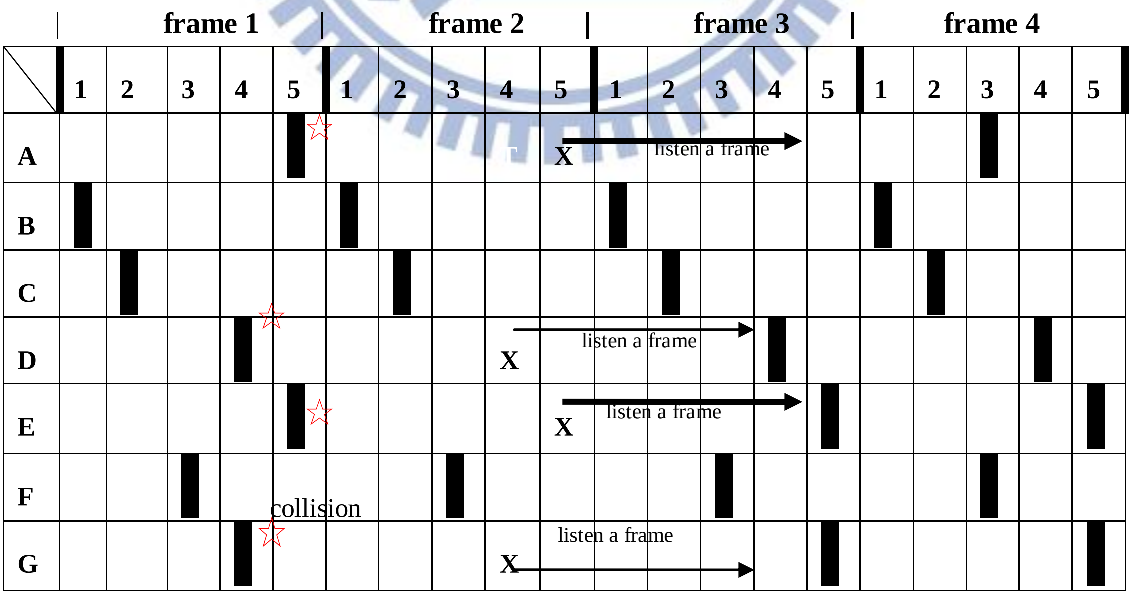


Figure 22. Reserved slot of each node

Chapter 5

Simulation Results and Analysis

5.1 Simulation Environment

In this section, we compare the performance of the proposed PC-ALOHA MAC protocol with that of RR-ALOHA MAC protocol in ns-2 [23]. The duration of each simulation is 10 seconds. Each simulation runs 20 times. The data rate is 2 Mbps (802.11b). All nodes are assumed to be stationary and their maximum transmission ranges are 250 meters. The EFI frame length is fixed at 80 bytes. The slot time is fixed at 2ms. The numbers of default nodes are 100 nodes, and the deployment region is 1000*1000 meters.

5.2 Results Analysis

A). Frame size vs. Reserving rate:

First, the aim of this experiment is to study the reserving rate relate to the frame size. As shown in Figure 22, the number of nodes is inversely proportional to the percentage of reserved nodes on RR-ALOHA. On the other word, PC-ALOHA needs a fewer slots to achieve 100% reserving rate than RR-ALOHA in a dense network. A larger frame size may incur a larger delay since each node has to wait for a longer period of time before the next frame coming. Otherwise, the smaller frame size can update the message more quickly.

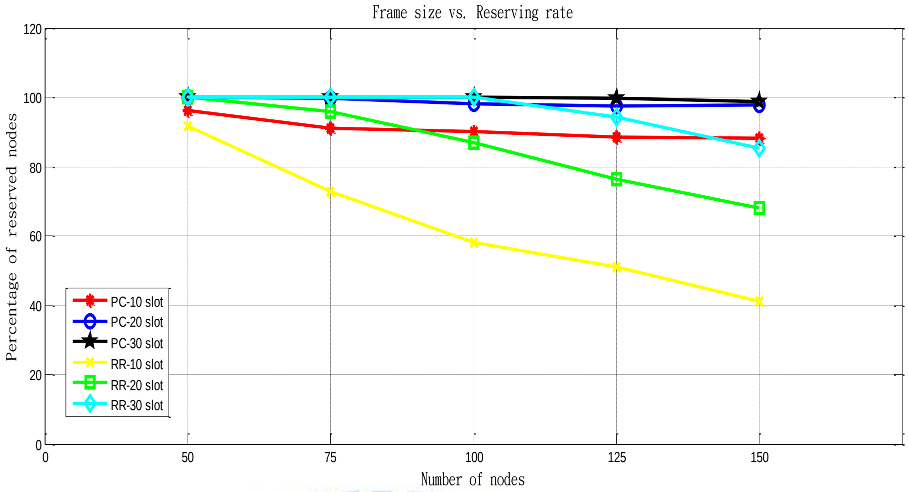


Figure 23. Frame size vs. Reserving rate

B) Single-hop performance:

As shown in Figure 23, RR-ALOHA requires 33 slots to achieve 100% of reserving rate, but PC-ALOHA requires only 28 slots to achieve 100% of reserving rate. PC-ALOHA can save about 15% frame size (28/33 =84.5%). PC-ALOHA frame size is smaller than RR-ALOHA, PC-ALOHA has a lower message update delay. It shows clearly, the slot reserving rate of RR-ALOHA is related to the frames size. PC-ALOHA always keeps the nodes reserving rate upon 98%. However, it is a dangerous when the channel is congestion in RR-ALOHA network. Because of many nodes have neither the right to transmit nor the guarantee of receiving packet from all its neighbors. In other words, the congestion nodes do not join to the network.

As shown in Figure 24, in order to enhance the slot reserving rate, PC–ALOHA need to reduce the transmissions range for slot time re-using. If the frame size is smaller, nodes will transmit at a smaller transmission range.

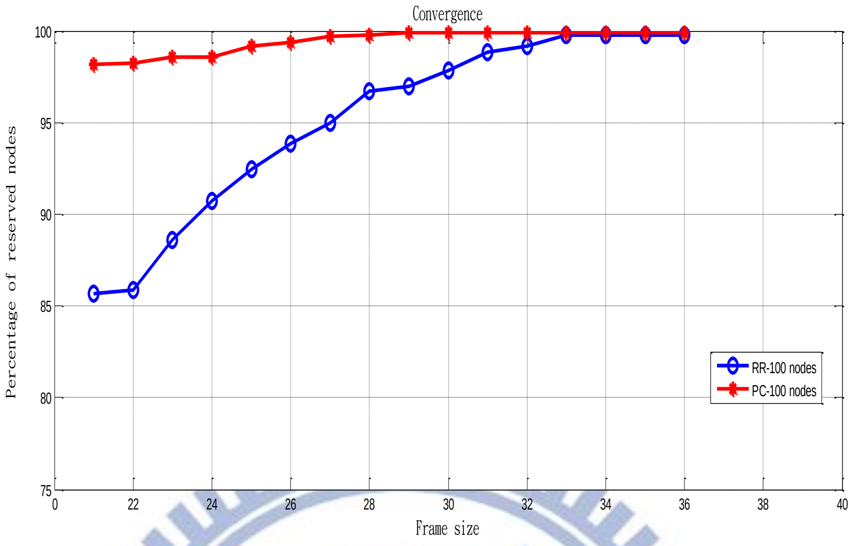


Figure 24. Reserving rate

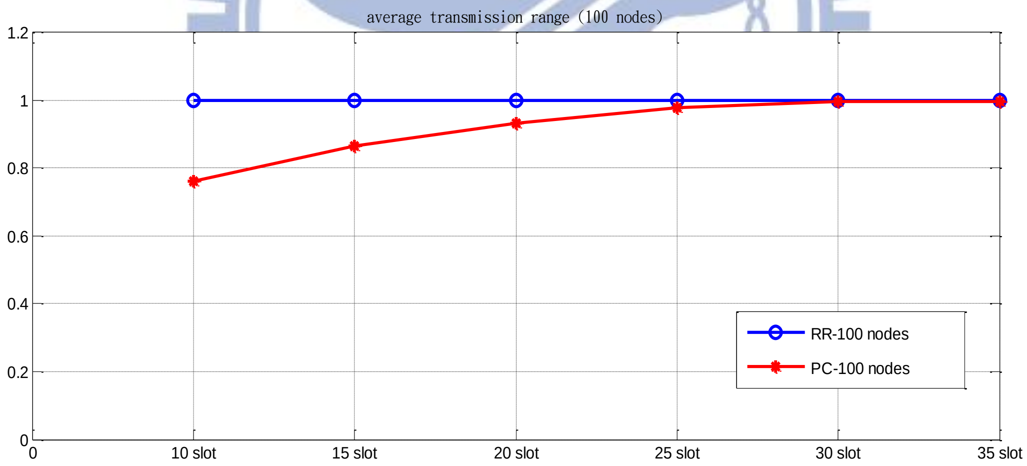


Figure 25. average transmission range

C) Convergence :

Although schedule-based MAC protocol can provide each node a contention-free opportunity for data transmission without collision, the node still need to contend for slot reservation by using RR-ALOHA or PC-ALOHA. Especially when it comes to the initialization of the system, in which many vehicles want to reserve a slot. As a result, it may take several frames until all the reservation processes complete.

As shown in Figure 25 and Figure 26, the RR-ALOHA protocol slot reserving rate almost can upon 100%. It means that the channel is not congestion. So the power control mechanism did not need to be triggered often. As a result, the PC-ALOHA will not increase the system convergence overhead compared to RR-ALOHA protocol.

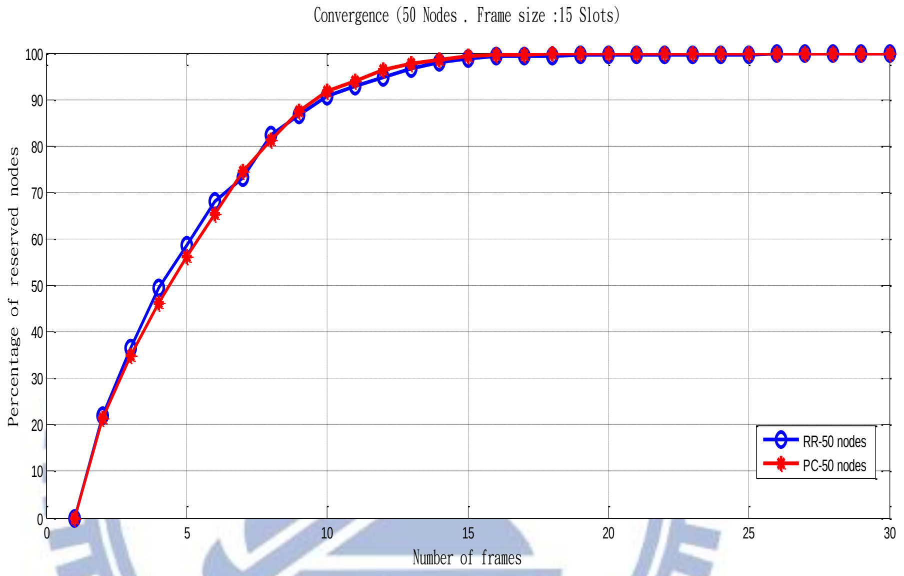


Figure 26. Convergence (50 Nodes)

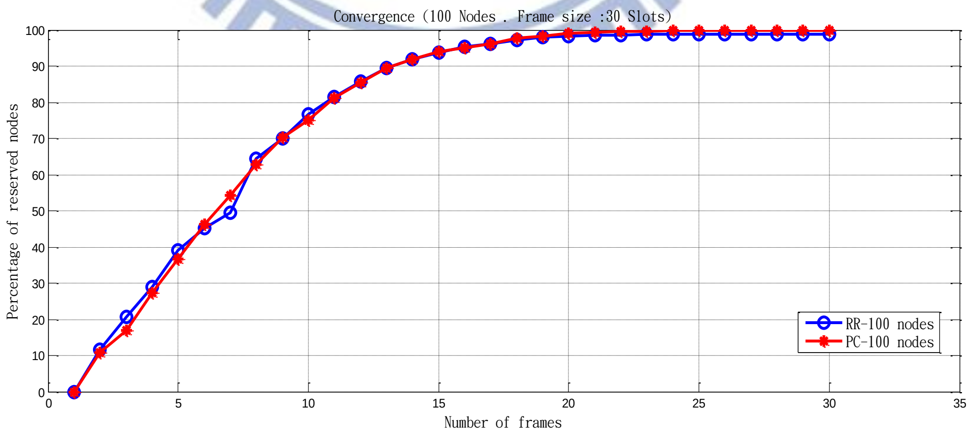


Figure 27. Convergence (100 nodes)

D) Performance under 100% reserving ratio:

As shown in Table 4, the relationship between slot reserving ratio of nodes and the number of frame sizes, average flooding hop counts and number of frame sizes, and average relaying delay and number of frame sizes in the different network density. There are two values in each field. Above number in the field presents the average value and below number in the field presents the maximum one. (e.g., the RR-ALOHA requires 32 slots upon 100% reserving ratio and the maximum number of slot is 33. PC-ALOHA only requires 26.2 slots upon 100% reserving ratio and the maximum number of slot is 28). As a result of the simulation: in the deployment region, the frame sizes under 100% slot reserving ratio is based on the nodes density. The results show that the PC/RR ratio of required slots decreases as the number of nodes increases, since the higher density, the larger frame size is required, which implies that our approach has more chance to find a free slot by reducing the node's power. On the other hand, PC–ALOHA will save a larger percentage of frame sizes in the high dense networking.

node	Required slots			Hop counts			Relaying delay (ms) (Hop count*Frame size)		
	RR	PC	PC/RR	RR	PC	PC/RR	RR	PC	PC/RR
50	14.200 (15)	12.666 (13)	0.89 (0.87)	3.328 (3.430)	3.417 (3.529)	1.026 (1.028)	95 (103)	87 (92)	0.915 (0.893)
100	32.000 (33)	26.200 (28)	0.82 (0.85)	2.969 (3.006)	3.027 (3.052)	1.019 (1.015)	190 (198)	159 (171)	0.836 (0.863)
150	46.500 (48)	35.800 (38)	0.77 (0.79)	2.917 (2.988)	3.032 (3.082)	1.039 (1.031)	271 (287)	217 (230)	0.800 (0.801)

Table 4. Performance under 100% reserving ratio

E) Flooding Delay

We analyzed transmissions delay problem with the maximum frame size above simulation case (e.g., 100 nodes frame size is 33 in RR-ALOHA, 28 slots in PC-ALOHA). As shown in Figure 27, (1) in dense networking, RR-ALOHA average delay is higher than PC-ALOHA. (2) The maximum delay in 150 nodes simulation case, RR-ALOHA is higher than PC-ALOHA about 28% and the average delay is about 11%. Therefore, it is a serious issue for safety-critical application message exchange.

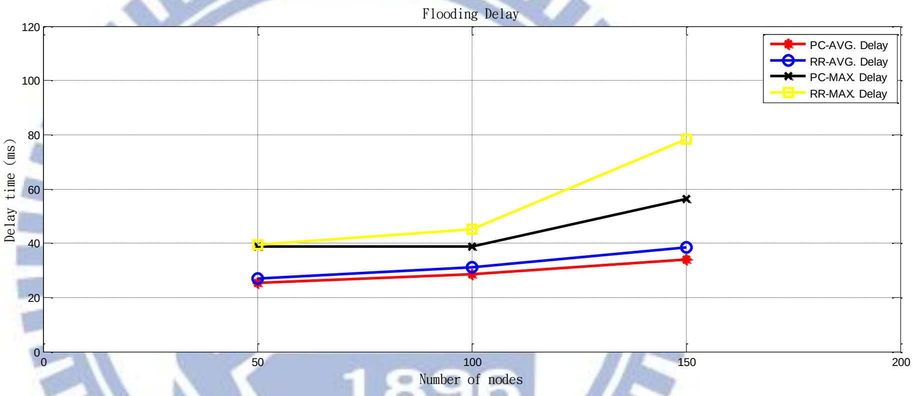


Figure 28. Flooding Delay

Chapter 6

Conclusion

In this paper, we have proposed a low-delay distributed TDMA Protocol with congestion control for wireless Ad Hoc networks base on previous RR-ALOHA MAC protocol. The most important features of PC-ALOHA MAC protocol are resolving the congestion problem and at the same time achieving a lower end-to-end delivery delay for the Ad Hoc networks. At same time, our PC-ALOHA MAC protocol guarantees the network connectivity even if transmission range of some nodes were reduced. As the result, in dense networking, our protocol decreases at most 28% in delay than RR-ALOHA. It proof our MAC protocol is suitable for the current delay-sensitive safety application, such as Cooperative Collision Avoidance (CCA) in vehicular networks. In future, we will further consider how to assign slots to nodes most quickly and a fewer convergence time in a dense network.

Reference

[1] X. Yang, J. Liu, and F. Zhao, "A Vehicle-to-vehicle Communication Protocol for Cooperative Collision Warning", *In Proceeding of the 1st Annual International Conference on Mobile and Ubiquitous Systems Networking and Services, IEEE Computer Society, Massachusetts*, USA, pp. 114 - 123, **2004**.

[2] V.S. Raghavan S. Kumar and J. Deng. "Medium access control protocols for ad-hoc wireless networks: A survey." *Elsevier Ad-Hoc Networks Journal*, 4(3): pp. 326 - 358, May **2006**.

[3] L. Armstrong, "Dedicated Short Range Communications (DSRC)," [Online]. Available: http://www.leearmstrong.com/dsrc/DSRCHome.htm

[4] M. Torrent-Moreno, P. Santi, and H. Hartenstein, "Fair Sharing of Bandwidth in VANET", in *Proceedings of the 2nd ACM International Workshop on Vehicular Ad Hoc Networks (VANET), Cologne, Germany*, pp. 49 - 58, **2005**.

[5] Xu Guan, Raja Sengupta, Hariharan Krishnan, Fan Bai "A Feedback-Based Power Control Algorithm Design Based Power Control Algorithm Design for VANET", *Mobile Networking for Vehicular Environments*, pp. 67 – 72, **2007**.

[6] J. Zang, L. Stibor, et al. "Congestion Control in Wireless Networks for Vehicular Safety Applications", *In Proceeding The 8th European Wireless Conference*, Paris, France. pp. 7, **2007**.

[7] Fan Yu and Subir Biswas, "Self-configuring TDMA protocol for enhancing vehicle safety with DSRC based vehicle-to-vehicle communication", *IEEE Journal Selected Areas in Communications*, vol. 25, no. 8, pp. 1526 – 1537, **2007**.

[8] Hassan-Aboubakr Omar, Weihua Zhuang, and Li Li, "VeMAC: A novel multichannel MAC protocol for vehicular ad hoc networks", *in Proc. of IEEE*

Conf. on Computer Communication Workshop, pp. 413 – 418, **2011**.

[9] F. Borgonove, A. Capone, M. Cesana, and L. Fratta, "ADHOC MAC: New MAC architecture for ad hoc networks providing efficient and reliable point-to-point and broadcast services", *Wireless Networks*, vol. 10, pp. 359 – 366, **2004**.

[10] Ning Lu, Xinhong Wang, Ping Wang, Peiyuan Lai, Fuqiang Liu "A distributed reliable multi-channel MAC protocol for vehicular ad hoc networks", *in Proc. of IEEE Intelligent Vehicles Symposium*, pp. 1078 – 1082, **2009**.

[11] Ning Lu, Yusheng Ji, Fuqiang Liu, and Xinhong Wang "A dedicated multi-channel MAC protocol design for vanet with adaptive broadcasting", *WCNC*, pp. 1 -6 ,**2010**.

[12] Jia Liu, Fengyuan Ren, Limin Miao, Chuang Lin "A-ADHOC: an adaptive real-time distributed mac protocol for vehicular ad hoc network", *ChinaCOM*, pp. 1 – 6, **2009**.

[13] F. Borgonovo, A. Capone, M. Cesana, L. Fratta, "RR-ALOHA, a Reliable R-ALOHA Broadcast Channel for Ad Hoc Inter-Vehicle Communication Networks", *Med-Hoc-Net*, Baia Chia, Italy, **2002**.

[14] B. Hull, K. Jamieson, and H. Balakrishnan, "Mitigating Congestion in Wireless Sensor Networks", *In Proc. of 2nd ACM Conference on Embedded Networked Sensor Systems*, pp. 134-147, November **2004**.

[15] W. Crowther, R. Rettberg, D. Waldem, S. Ornstein, and F. Heart, "A System for Broadcast Communication: Reservation-ALOHA," *in Proceedings of the Sixth Hawaii International Conference on System Sciences*, January **1973**.

[16] F. Borgonovo, L. Campelli, M. Cesana, and L. Fratta, "Impact of user mobility on the broadcast service efficiency of the ADHOC MAC protocol", *Proc. IEEE VTC*, vol. 4, pp. 2310-2314, **2005**.

[17] Marc Torrent-Moreno, Jens Mittag, *Student Member* "Vehicle-to-Vehicle

Communication: Fair Transmit Power Control for Safety-Critical Information", *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY*, VOL. 58, NO. 7, pp. 3684 – 3703, **2009**.

[18] M. Torrent-Moreno, P. Santi, and H. Hartenstein, "Distributed fair transmit power adjustment for vehicular ad hoc networks." *In SECON '06 3rd Annual IEEE Communications Society*, pp. 479-488, **2006**.

[19] J. Mittag, F. Schmidt-Eise nlohr, M. Killat, J. Harri and H. Hartenstein,"Analysis and Design of Effective and Low-overhead transmission power control for VANETs." *in Proc. 5th ACM Int. Workshop VANET*, pp. 39-48 , **2008**.

[20] Ghassan Samara, Sureswaran Ramadas, Wafaa A.H. Al-Salihy "Safety Message Power Transmission Control for Vehicular Ad hoc Networks"**,** *J. Computer Sci., 6 (10): 1027*-1032, **2010**.

[21] Chunxiao Chigan and Jialiang Li "A Delay-Bounded Dynamic Interactive Power Control Algorithm for VANETs", *IEEE ICC*, pp. 5849 – 5855, **2007**.

[22] K.R. Gabriel and R.R. Sokal. *"A New Statistical Approach to Geographic Variation Analysis." Systematic Zoology*, vol. 18, pp. 259 - 278, **1969**.

[23] "The network simulator (NS2) ", http://www.isi.edu/nsnamlns/

[24] T. Liu, J. A. Sylvester, and A. Polydoros, "Performance evaluation of R-ALOHA in distributed packet radio networks with hard real-time communication," in *Proc. IEEE Veh. Technol. Conf.*, pp. 554 - 558 vol.2 **1995**.

[25] R. Verdone, "Multihop R-ALOHA for intervehicle communications at millimeter waves", *IEEE Trans. Veh. Technol.*, no. 4, pp. 992 – 1005, **1997**.

[26] Y. Wang and B. Bensaou, "Achieving fairness in IEEE 802.11 DFWMAC with variable packet size," *in Proc. IEEE Global Telecommun. Conf.*, pp. 3588 - 3593 vol.6, **2001**.

[27] W. Crowther, R. Rettberg, D. Waldem, S. Ornstein and F. Heart, A system for

broadcast communications: Reservation ALOHA, in: *Proceedings of 6th Hawaii Internat. Conf. Sist. Sci.*, pp. 596–603, **1973**.

[28] Flaminio Borgonovo, Luca Campelli, Matteo Cesana “Topology Control In Ad Hoc Networks: A MAC Layer Solution”, *International Journal on Wireless {&} Optical Communications, VOL. 3, NO. 1*, pp. 101 – 117, **2006**.