무선인지 애드혹 네트워크를 위한 MAC 프로토콜 비교 분석

(A Comparative Survey on MAC Protocols for Cognitive Radio Ad Hoc Networks)

Sunil K. Timalsina*, 모 상 만**

(Sunil K. Timalsina and Sangman Moh)

요약

무선인지 네트워크에서 비면허 사용자는 면허 스펙트럼 대역을 감지하여 가회가 있을 때마다 면허 사용자에 간섭을 일으키지 않고 매체에 접근한다. 특히 애드혹 네트워크에서는 MAC 계층이 비면허 사용자들간 스펙트럼 접근을 조정하는 중요한 역할을 수행한다. 이에 따라 최근 많은 MAC 프로토콜이 연구되고 있다. 본 논문에서는 무선인지 애드혹 네트워크에서의 MAC 프로토콜을 비교 분석한다. 먼저 프로토콜들을 공통 제어 채널을 기준으로 분류하고 각 종류별 주요 프로토콜을 분석한다. 그리고 나서 프로토콜들을 고유 특성과 성능 측면에서 정성적으로 비교한다.

■ 중심어 : | 무선인지 | 애드혹 네트워크 | MAC | 공통 제어 채널 | 동적 스펙트럼 접근 |

Abstract

In cognitive radio networks (CRNs), unlicensed users sense the licensed spectrum bands and opportunistically access them without interfering operations of licensed users. Especially, in ad hoc networks, the MAC layer plays an important role in coordinating unlicensed users access to the spectrum and, thus, a number of MAC protocols have been studied recently. In this paper, we comparatively examine MAC protocols in cognitive radio ad hoc networks (CRAHNs). First, we categorize the protocols on the basis of common control channel (CCC) requirements and further review major implementations for each category. Then, we make a qualitative comparison of the protocols in terms of inherent characteristics and performance.

■ Keywords : | cognitive radio | ad hoc network | MAC | common control channel | dynamic spectrum access |

I. Introduction

Recently, the scope and usage of wireless devices have increased exponentially. A multitude of wireless networks, such as Wi-Fi, Bluetooth, TV, cellular network, etc., utilize various spectrum bands. Normally an authority (usually, the government) 'licenses' these spectrum bands. But, according to the report by Federal Communication Commission (FCC) [1], less than 30% of the already-allocated spectrums are utilized even in densely populated areas. Mitola and Maguire [2] suggested cognitive radio (CR) technology for using radio spectrums when they are not occupied by licensed users.

Since the term 'Cognitive Radio' has been coined in 1999, researches have contributed a lot into the problem. In order to utilize TV white spaces, IEEE has developed IEEE 802.22 standard for CRNs [3]. Some authors like Yuan et al. [4] have proposed a prototype along with MAC protocol and a hardware platform. Pawelczak et al. has illustrated the development of a CRN in past years in reference [5]. The standardization efforts make it possible to provide a protocol stack along with the guideline for developing new protocols. Most MAC protocols have tried to use a network-wide common control channel (CCC) for exchanging control signals and synchronizing

* 학생회원, 조선대학교 컴퓨터공학부, sunil.timalsina@gmail.com

**정회원, 조선대학교 컴퓨터공학부

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within/between the networks [6]-[9]. Some has also coined problems in CCC and hence tried to avoid using CCC as in references [10]-[11].

In this paper, MAC protocols for CRAHNs are classified into three categories as follows: dedicated CCC (D-CCC), non-dedicated CCC (ND-CCC) and non-CCC (N-CCC) on basis of CCC requirement, and reviewed in terms of operational principles and characteristics. Then, they are compared qualitatively with respect to major characteristics and achievable performance. The comparison shows that D-CCC protocols work well in homogeneous environments with sparsely populated networks. N-CCC protocols outdo D-CCC protocols in networks with dissimilar channel allocation. However, there is very few, moderate and high reconfiguration and signal transmission overhead in D-CCC, ND-CCC and N-CCC based protocols respectively.

The rest of the paper is organized as follows: Section II outlines design issues with MAC protocols in CRAHNs. Section III offers a classification of MAC protocols for CRAHNs on the basis of CCC requirements and major protocols in each category followed by their quantitative comparison in Section IV in terms of characteristics and performance. Finally, the paper is concluded in Section V.

Ⅱ. Design Issues with MAC Protocols in CRAHNs

1. Spectrum Sensing

Spectrum sensing is an important characteristic of CRAHNs. It has two basic purposes: one is to find out available spectrum and the other is to detect PU activities. Sensing the channel for identification of PU activities is called *inband sensing*; whereas finding a new spectrum is called *out-of-band sensing*. In literature, different sensing methods have been discussed [14] such as *energy detector based, waveform-based, cyclostationary-based, radio- identification based* and *matched-filtering sensing*. The dissemination of sensing results can be done in a centralized or distributed manner. In the centralized distribution, a central coordinator transfers sensing information to network members. On the other hand, in the distributed method, all members exchange their sensing results among themselves. Spectrum sensing also depends on hardware constraints. The major design factors are sensing time and the number of radios.

2. Dynamic Spectrum Allocation

CRAHNs are subject to the heterogeneous environment with different channel availability. This heterogeneity is due to such factors as time and location of different nodes and PU activities. Therefore, spectrum allocation is of critical importance. In MAC protocols with CCC, channel allocation is advertised to the neighbors through CCC. If there is no CCC (e.g. AMAC [12]), channel allocation list is exchanged among sender-receiver pairs.

3. Dynamic Spectrum Sharing

In reference [15], spectrum sharing is classified into three modes: *underlay, overlay* and *interweave*. In the underlay mode, SUs utilize the spectrum being used by PUs below some signal threshold level. This threshold level limits SUs transmission from interfering with the PUs transmission. In the overlay mode, CR users try to either cancel or reduce the interference on both SU and PU side by utilizing their information of non-CR users' messages. Finally, in the interweave mode, the SU transmits only within the vacant portions of the spectrum. Therefore, to avoid the interference, it immediately retainsits transmission as soon as PU arrives.

4. Common Control Channel

Although several MAC protocols for CRAHNs are based on availability of the CCC, due to different types of channels available to nodes in a network, MAC protocols without CCC are also used. CCC plays an important role as it is used for coordination and control signal transmission. But this also introduces jamming and contention of the transmission.

5. Other Issues

As CR research is still in its infancy, there are several issues to be addressed in terms of MAC protocol design. The mobility of nodes brings on new challenges as it requires network reconfiguration and extra overhead during signal transmission. Also, it is still an open question how to handle channel switching and spectrum handoff arising from spectrum mobility. In addition, the number of radios in the device can play a critical role in spectrum sensing accuracy and energy constraints at the same time. Also, the capability of a radio to sense the wide spectrum, delays in channel switching and spectrum heterogeneity are still the areas that need to be considered. In dense networks, there is also a problem of hidden terminals (in addition to exposed terminal.)

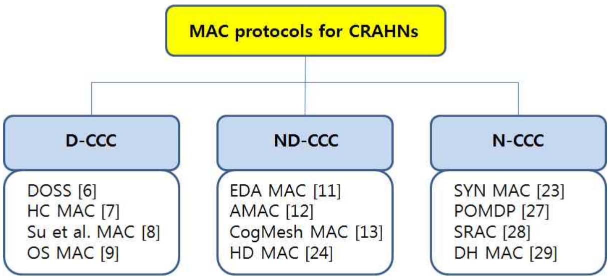

Fig. 1. Classification of MAC protocols for CRAHNs based on CCC.

II. MAC Protocols for CRAHNs

In CRAHNs, access to the opportunistic spectrum is coordinated by the MAC protocol. In legacy MAC protocols, contenders contend on CCC by using protocols like CSMA/CA [16] and get access to the channel upon winning the contention. However, in CRAHNs, the CCC might not be available or can be reclaimed by PUs. Papers [17]-[22] have studied and distinguished MAC protocols in CRAHNs. Here we classify MAC protocols for CRAHNs into three major categories (See Fig. 1): dedicated CCC (D-CCC), non-dedicated CCC (ND-CCC) and non-CCC (N-CCC).

- **Dedicated CCC:** The D-CCC protocols assume that CCC is available to all network members. This can be either a channel licensed by the corresponding CRN authority or may as well exist in some unlicensed band such as ISM. SUs contend in this D-CCC for channel access.
- **Non Dedicated CCC:** The D-CCC based MAC protocols are simple but sometimes they cannot be realizable. This is because in some scenarios CCC cannot be guaranteed. In addition, CCC is prone to *common control channel saturation problem* and *jamming* [23]. In case of large number of contenders, control channel can get saturated. The ND-CCC has dedicated CCC at the network startup but a CCC is established dynamically. This can be done either by selecting one of the available channels as CCC [11], [12] or by forming groups within a network and selecting different CCCs in each group [13], [24].
- **Non-CCC:** The N-CCC based MAC protocols do not require any CCC to control signal exchange. Usually, intending sender would tune to the receivers' data channel and transfer control and data packets over the same channel. In some cases, channel hopping is used. Control signals are passed by hopping on different channels. These mechanisms reduce the overhead of selecting CCC in ND-CCC based MAC protocols, but require additional network-wide synchronization.

1. MAC Protocols based on D-CCC

1.1. DOSS MAC

The Dynamic Open Spectrum Sharing (DOSS) [6] protocol is based on setting up three operational frequency bands and hence requires three transceivers per node. Three channels, namely, *common control channel*, *data channel* and *busy tone channel* are assigned to three radios respectively. In CCC, control signals are transmitted whereas data band is a wide band used for data transmission. A narrow band called busy tone band has one to one mapping with data band. The corresponding busy tone band is set before data transmission in data channel so that rest of the network elements are well informed about data channel being used.

Although using the busy tone band helps to solve the hidden node problem, it demands a considerable amount of extra bandwidth for signaling purpose only. In addition, if the busy tone band is reclaimed by PU, the busy tone for ongoing data transmissions can be lost that can result in collisions. Another major disadvantage of DOSS is the use of three transceivers per node that adds on to the device cost and power efficiency.

1.2. HC MAC

The Hardware Constrained MAC considers the existing hardware constraints in practical CRs [7]. It is that the current CR devices can sense only limited range of spectrum with certain duration and can utilize even lesser spectrum out of sensed spectrums. In addition, more of the sensing implies more opportunity in one hand and more overhead in the other. Therefore, a stopping rule is implied for sensing.

It works by dividing time into three phases: *contention*, *sensing* and *transmission*. With C-RTS and C-CTS signals, intending pairs win a contention and overhearing nodes defer the transmission during contention phase. After that, the pair senses channel till some stopping time which is same for both and exchange S-RTS and S-CTS signal during sensing phase. This is finally followed by data transmission in transmission phase.

This protocol considers the existing cognitive radio constraints and maximizes the throughput by only sensing a number of channels as much possible. However, an extra number of control messages are exchanged during each phase as compared to the legacy MAC protocols. This could lead to control channel saturation problem faster than in with the legacy protocols. Besides, as only single transceiver is used, the intended receiver can be busy with its own data transmission just when the sender sends the request.

1.3. Cross-Layer based MAC

The Cross Layer Based MAC integrates spectrum sensing policy at the physical layer and packet scheduling at MAC layer [8]. It is based on two transceivers: one for dedicated CCC and another for spectrum sensing and data transmission. The licensed channels are divided into slots which represents either ON or OFF state of PU if it is active or idle respectively. The CCCs time axis is further divided into the slots of the same length as that of the licensed channels and are further synchronized with the licensed channels slots. The slots in CCC are further divided into *reporting phase* and *negotiating phase*. During n mini slots in reporting phase, each SUs senses licensed channel and informs to control transceiver whereas during negotiation phase, SUs negotiate for transmitting data using contention based algorithm similar to IEEE 802.11 DCF and p-persistent CSMA.

When the number of SUs increases, CCC can become saturated because of the high number of contentions. Also, all channels are used by a single pair in the slot that makes other pairs to wait for the next slot to contend.

1.4. OS-MAC Protocol

OS-MAC [9] assumes that each SU is equipped with a single half-duplex radio. A D-CCC and N non-overlapping data channels (DCs) with equal bandwidth are assumed to be available. Time is divided into periodic *opportunistic spectrum period* (OSP). OSP is further divided into three phases: *select phase*, *delegate phase* and *update phase*. Two or more set of users who want to communicate with each other forms a SU group (SUG). The control frames belonging to different channels is communicated via D-CCC whereas those belonging to same DC (and hence SUG) is communicated via DC.

Each SUG has a delegate SU (DSU) responsible for information exchange between other DSUs of other SUGs regarding state of other DCs. Only one member of a SUG can transmit data at a time using mechanism similar to IEEE 802.11 DCF without using RTS/CTS packets. Rest of the members of SUG would only receive data and one of them send back ACK signal for reception of packet.

Therefore, OS-MAC assumes that the SUs can be divided into several groups according to their channel availability and allows only one group member to send data, while the others are receiving it. The selection and DSU contention, however, are the major overheads of this protocol.

2. MAC Protocols based on ND-CCC

2.1 EDA-MAC

Hsu et al. have proposed the EDA-MAC [11] protocol to modify C-MAC [10] protocol for faster join process of network members and increase throughput. If a SU finds a communication group, it can start join process to join that group. Otherwise, it forms the communication group and become the leader. Channel chosen to form a communication group is called *rendezvous channel*. A channel is divided into consecutive superframes each in turn containing a *beacon period* (BP) and a *data transmission period* (DTP). Each BP contains one to several signalling phases (SP), a beacon phase, and a CTS phase. Each SP contains several signalling slots during which host intending to join the group will contend to transmit a signal in one of the signalling slots.

In the dedicated beacon slot, intended sender sends RTS with rate subfield. Leader also assigns a dedicated CTS slot for receiver to avoid collision. After leader listen the CTS signal, it schedules transmission according to the various priorities such as smallest data first or least number of transmissions first etc. For load balancing, leader also manages channel switching of nodes. First node joining new channel becomes leader of that channel which periodically switch back to RC for re-synchronization. In addition, it also undergoes primary user detection during quite periods (QP) within DTP.

The EDA MAC protocol greatly improves C-MAC protocol by introducing a leader for coordination. At the same time this incurs an extra overhead to the leader as it is responsible for managing separate timings for beacon period starting time (BPST) and non-overlapping quite periods (QPs) among the channels. Also, due to dynamic length of the beacon period, throughput is reduced significantly when the number of the contending users increases as this makes the DTP smaller.

2.2. AMAC

Joshi et al proposed the AMAC protocol [12] which does not need an extra D-CCC throughout the network. Hence, they suggest a mechanism to overcome the *common control channel saturation problem*. The AMAC protocol assumes that there are n available channels in the environment. Every node prioritizes the available channels according to channel reliability: $C_1, C_2, \ldots, C_n$. Here, C_1 is the most reliable channel, C_2 is the second, and so on, and C_n is the least reliable channel. This list is called the *indexed channel list* (ICL).

When a sender wants to transmit, it sends the RTS signal with its ICL to the receiver. When the receiver receives the RTS signal, it compares the sender's ICL with its own ICL and creates a new list that includes only channels available to the both parties. This list is called ICCL (*indexed common channel list*). The receiver then sends back the CTS signal to the sender with this ICCL. From the ICCL, the most reliable channel is selected as *non-global common control channel* (NCCC) which is used to exchange control signals. The second reliable channel becomes the data channel to transmit the data. Finally, the third reliable channel is used as the data backup channel.

However, the mechanism for sending ICL to the receiver during the initialization phase is not defined in this protocol (ex. a channel through which an ICL could be sent). Also, it requires at least three common channels between the communicating pairs for starting communication that might not be feasible at all time in a network with heterogeneous channel availability. Besides, it reserves one additional channel for backup channel that again takes valuable resource.

2.3 CogMesh MAC Protocol

In [13], Chen et al have proposed cluster-based network architecture for CRAHNs and CogMesh MAC protocol where the SUs form clusters. There is no global CCC available but each cluster has a local CCC called master channel. A leader forms a cluster and becomes a clusterhead. It invites neighboring nodes to join the cluster. To interconnect the clusters, one node is selected as a gateway node, which may or may not be the common node between two or more clusters. Hence, considering the rest of nodes called ordinary nodes, there are three types of nodes in each cluster. The control signal transmission is done in the master channel. It consists of MAC superframes which are further divided into a number of periods as *beacon period* (BP), *Neighborhood broadcasting period* (NBP), *data period* (DP), q*uite period* (QP), *private* and *public random access period* (Private and Public RAP).

The CogMesh MAC protocol aims at avoiding the global CCC by using a local CCC (master channel) within a local group. But this channel is also prone to common control channel saturation problem. Also, when a PU reclaims the master channel, the cluster has to undertake the reformation. This reformation would require a lot of time and valuable resource by SU which is an extra undesirable overhead for a network.

2.4 HD MAC

In HD-MAC, coordination groups are formed within a network based on available common channels [24]. Members within same group are only allowed for direct communication whereas *bridge nodes* which have common channels to both groups realize communication between those groups. For establishing a coordination group, every user scans the available channels and then beacons its channel list over the available channels. This is called *neighbour discovery* and allows each node to accumulate information on its neighbouring nodes and channel availability. Among the available channels, a channel with the highest connectivity (i.e. channel shared by the maximum number of nodes) is selected as a local coordination or control channel for that group through the process of voting. To handle spectrum heterogeneity in the CRNs, authors have proposed a modification to the legacy MAC protocol MMAC [26] for ad hoc networks.

Therefore, HD MAC aims at highest connectivity in the environment where the possibility of finding a common channel between every SUs in the network is very low. This protocol, however, experiences the same network reconfiguration problem when a PU arrives at the selected local coordination channel as in CogMesh MAC protocol.

3. MAC Protocols based on N-CCC

3.1. SYN MAC

In [23], Kondareddy et al. have proposed the SYN-MAC protocol. It assumes that each SU is equipped with two radios. One radio is called *listening radio* and is used for listening control signals and another is called *data radio* which is used for data transmissions. The environment is heterogeneous i.e. channel availability is not the same for all SUs.

When a SU wants to start data transmission over a channel, it waits for the time slot represented by the channel. Within that slot, the sender transmits the RTS signal after a backoff time. When it successfully receives the CTS signal from the receiver, data transmission starts immediately. As the receiver and the other nodes listen to the same channel at this particular time slot, overhearing nodes are aware that the channel is in use by the specific communicating pair. So, the overhearing nodes avoid to transmit into this channel.

Therefore, this protocol ensures connectivity between the two nodes even if they have only one common channel. But here, every SU node must know all the available channels in advance so it could divide the time slots. Also, channels are not utilized until their corresponding time slot arrives.

3.2. POMDP

DC-MAC [27] is based on *partially observable Markovian decision process* (POMDP). The spectrum is accessed by combining the spectrum sensing at physical layer and with the past statistics. Channels can be assumed to be in two states based on primary users activity as either in state '1' if it is busy or '0' if it is active. These states of channels are used for POMDP for deducing channel access opportunity. Time is divided into number of slots for data transmission using CSMA protocol by using RTS/CTS packets for handshaking and DATA/ACK for data transmission. For selecting channel the best channel, a decision is made based on sensing results (current and past). As it is assumed that both sender and receiver are subject to same channels environment and are using same decision process, they would select the same channel for transmission for next transmissions.

The authors also have assumed that the state of the channels (PU slots and transition probability) would be known that might be difficult to implement, however. The hidden and exposed node problem also was not addressed.

3.3. SRAC

SRAC proposed by Ma et al. in [28] is based on cross-channel communication in the single-radio multi-hop ad hoc networks. A SRAC algorithm is proposed which provides results based on detection of either jammer or PU and channel load to legacy MAC protocols. Authors propose to avoid interference to transmitter as long as it does not pose interference to PUs.

Every node selects a stable *receive channel* among available channels for receiving data. Nodes also maintain database about receive channels of its neighbors. Data transmission can be done using the legacy CSMA/CA MAC protocol on corresponding receive channels.

This protocol introduces a novel cross channel mechanism in CRNs. The sender broadcasts the RTS signal over all the receive channels in its receive channels list to avoid collision. But this incurs extra control signal transmission. In addition, in case of change in the receive channel of a node, this message is broadcasted over the network which is further an extra overhead.

3.4 DH-MAC

Shih et al. have proposed a non-CC based dynamic hopping MAC protocol (DH-MAC) [29] for CRNs. Each node in the network consists of a single CR transceiver. N non-overlapping orthogonal channels in the network are indexed as [0, N-1]. The nodes hop among these channels in a cyclic pattern (called *l* cycles) staying in one channel for T time interval. The channel hopping (CH) sequence of nodes is determined by a parameter set called channel hopping (CH) parameter set. This parameter set is broadcasted in the beacon at the start of each time interval T and also embedded in the packet header.

This protocol provides solution to CCC problems by using hopping technique and fast channel switching in case of unavailability. It also guarantees that the pair would find at least one rendezvous channel in every cycle. But this requires extra overhead of synchronization between the nodes so that the neighbors' parameters are not same. Also the hopping process requires hardware provison for fast switching between the channels.

IV Comparison and Discussion

While designing a MAC protocol for CRAHNs, we should consider a great deal of important features. The brief comparison of these protocols is shown in Table 1. The non-CCC based network is easy to deploy as it does not require pre-allocation of channel (CCC). But due to mobility in either the nodes or the spectrum, networks need to be reconfigured with the group based or non-CCC protocols. This would require extra reconfiguration effort and coordination between the nodes. The most advantageous feature of the ND-CCC based and N-CCC based protocols is that they are very flexible, even in networks with heterogeneous channel availability. As discussed previously, however, in D-CCC based protocols, as the number of nodes increases, the demand in control signal transmission increases as well. This leads to a high contention in accessing CCC and results in the CCC saturation problem. This is less probable in ND-CCC based protocol and negligible in N-CCC based protocols. The increased number of users and hence the increased network density renders it more prone to hidden terminal problems. As the neighborhood discovery is very difficult in non CCC based protocols, hidden terminal problems are more prominent there.

In addition to the above, the performance of MAC protocols for CRAHNs is also greatly affected by the number of available radios. The more is the number of radios, the better is the accuracy of channel sensing and the multichannel hidden terminal problem is better addressed at the same time, although the cost and power consumption go up. Sensing policies and support of multi-hop networks are also needed to be considered. Table 2 comparatively summarizes the protocols discussed in this paper.

V. Conclusion

In this paper, we have presented some major CR MAC protocols for ad hoc networks and some state of art works and discussed main design issues. In addition to other challenges, spectrum sensing and spectrum allocation along with spectrum handoff are the key issues, which still need to be addressed. We divided and explained these protocols on the basis of their CCC requirements. In the course of our examination, we found that most of the earlier works were assuming CCC provision and extension to legacy ad hoc MAC protocols. But recently, several alternatives have been proposed where CCC is not used as it is less likely to be found in the network. However, the proposed protocols still have a number of shortcomings and require lots of enhancements.

In the future, researchers are expected to produce adaptive protocols, which could challenge dynamic environment and changing spectrum usage policies. In order to implement this, it is time to come up with support of security and cooperation in CRAHNs. With many licensed bands being opened for access by SUs, CRAHN MAC protocols specialized in utilizing these particular spectrums could be meaningful and implementable.

Table 1. Comparison of CR ad hoc MAC protocols based on CCC requirements

Feature	D-CCC	ND-CCC	N-CCC
Deployment	Difficult	Moderate	Easy
Network re-configuration overhead	Less	High	Very high
Channel allocation	Allocated to all the members	Allocated within groups	Sparsely allocated
Heterogeneous channel allocation	Less affected	Re-formation of groups	Supported
Synchronization between nodes	Done through CCC	Few protocols implemented (eg. [11])	Less needed
Control signal transmission overhead	Very high	Moderate	Less
CCC saturation problem	Very high	Few	Very less
Hidden terminal problems	Can be tackled using CCC	Moderate	High

Table 2. Discussed protocols

CCC	Protocol	Number of radios	Single/Multi hop
D-CCC	DOSS [6]	3	Multi
	HC MAC [7]	1	Multi
	Su et al. MAC [8]	2	Single
	OS MAC [9]	1	Single
ND-CCC	EDA MAC [11]	1	Not mentioned
	AMAC [12]	Not mentioned	Single
	CogMesh MAC [13]	Not mentioned	Multi
	HD MAC [24]	1	Multi
N-CCC	SYN MAC [23]	2	Multi
	POMDP [27]	1	Single
	SRAC [28]	1	Multi
	DH MAC [29]	1	Not mentioned

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저 자 소 개

Sunil K. Timalsina(학생회원)
2009년 Tribhuwan대학교 학사
2009년~2010년 iSystems 엔지니어
2010년~현재 조선대학교 석사과정

<주관심분야 : Wireless networks, ad hoc networks, cognitive radio networks, MAC, directional antenna>

모상만(종신회원)
2002년 KAIST 박사
1991년~2002년 ETRI 팀장
2002년~현재 조선대학교 교수

<주관심분야 : Mobile computing and wireless networks, ad hoc and sensor networks, cognitive radio networks, parallel and distributed systems>