A Survey of MAC Protocols Design Strategies and Techniques in Wireless Ad Hoc Networks

Amjad Ali, Wang Huiqiang, Lv Hongwu, and Xiaoming Chen
Harbin Engineering University, Harbin 150001, China
Email: amjadmsit@gmail.com; wanghuiqiang@hrbeu.edu.cn, lvhongwu@hrbeu.edu.cn, chenxiaoming@hrbeu.edu.cn

Abstract—Medium access control (MAC) protocols provide a means to nodes to access the wireless medium efficiently and collision free to the best of their ability. In this paper we provide a survey of MAC protocols developed for mobile ad hoc (MANETs) in the past based on certain methods and techniques such as multiple radios, multiple channels and specialized beamforming antennas. We discuss some of the MAC protocols designed for wireless sensor networks (WSNs) and their applicability in a MANET environment. There are some similarities between MANETs and WSN's in general but there is also critical differences between the two that affect the design of MAC protocols for both these networks. Traditionally, MAC protocols have been classified on the basis of two broad categories of contention free and contention based MAC protocols but a number of new algorithms proposed in the recent past merge the two schemes together in a single MAC solution and thus there is a need for a new classification approach. MANETs have their unique constraints and characteristics. In this classification, we will discuss various MAC solutions proposed in the past in the light of these constraints and characteristics. We do not intend to explain each and every protocol since the number of MAC solutions proposed in the past decade or so is very large. The purpose of this article is to give the readers a general idea on the various techniques and methods used in literature to develop MAC protocols for MANETs. The techniques range from algorithmic changes such as cross-layer design to enhancement in hardware such as directional antennas.

Index Terms—wireless ad hoc networks, wireless sensor networks, medium access control protocols, throughput, cross layer design, multi channel MAC

I. Introduction

A number of MAC protocols have been developed for MANETs in recent years. Fig. 1 shows a classification of MAC protocols for MANETs based on various strategies and techniques. We categorize MAC protocols based on two major design paradigms. The first category of MAC protocols is the single-radio MAC protocols and the other category is multi-radio MAC solutions. The techniques used in the single-radio MAC protocols include omnidirectional antennas, directional and beamforming antennas and different channel access methods including hybrid channel access methods such as a combination of TDMA and Frequency Division Multiple Access (FDMA). In the multi-radio category of MAC protocols where more than one radio devices are used for communication, various different methods have been used. Some multi-radio solutions have used a single radio interface for exchanging control and data and another out-of-band transceiver is used for synchronization purposes to coordinate an orderly exchange of data between nodes. In this type of MAC solutions, the out-of-band synchronization transceiver is not involved in the actual transmission of data but only assist nodes in coordinating their data exchange. In other multi-radio MAC solutions, two or more transceivers perform all the three tasks of exchanging coordination messages, control messages and actual data exchange. MAC protocols in the past have traditionally been categorized into contention based and contention free protocols but this classification has become more and more obsolete. A number of new MAC algorithms proposed recently use a mixture of the two mechanisms [1]-[3]. Combining the features of both the contention based algorithms such as Carrier Sense Multiple Access (CSMA) and contention free algorithms such as Time Division Multiple Access (TDMA) have proved to provide better results. Contention based and contention free methods have been applied to different parts of some MAC algorithms which has blurred the difference when we classify MAC protocols. In IEEE 802.11DCF [4] for example, the exchange of Request to Send (RTS) and Clear to Send (CTS) messages are contention based but once a node wins access to the channel, the actual transmission of data is contention free. A totally contention free algorithm such as TDMA is not suitable for use in a MANET environment because TDMA based systems are designed to work best in centralized environments. The time slot assignment can be best achieved when a central base station or access point assigns time slots to individual nodes in the network. For MANETs, a TDMA system that deals with time slots locally in a neighborhood would be an ideal solution given that there is no fixed infrastructure available in MANETs. We will discuss these channel access methods for individual protocols as we explain them latter in the paper. Another major reason for why we started our classification of MAC protocols from single and multiple radio devices per node is

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Corresponding author email: amjadmsit@gmail.com.
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because MANETs are very sensitive to energy consumption. Multi-radio MAC solutions can improve network performance and are also helpful in coordination between nodes but the cost of operating more than one radio device in MANETs cannot be ignored while developing such a solution. The rest of the paper is organized as follows. In Section II we discuss single-radio single-channel MAC protocols; in Section III we discuss multi-radio MAC protocols. In Section IV we discuss single-radio multi-channel MAC protocols and in Section V, we provide a discussion on the most important aspects of MANET MAC protocols that could impact its practical implementation and conclude this paper.

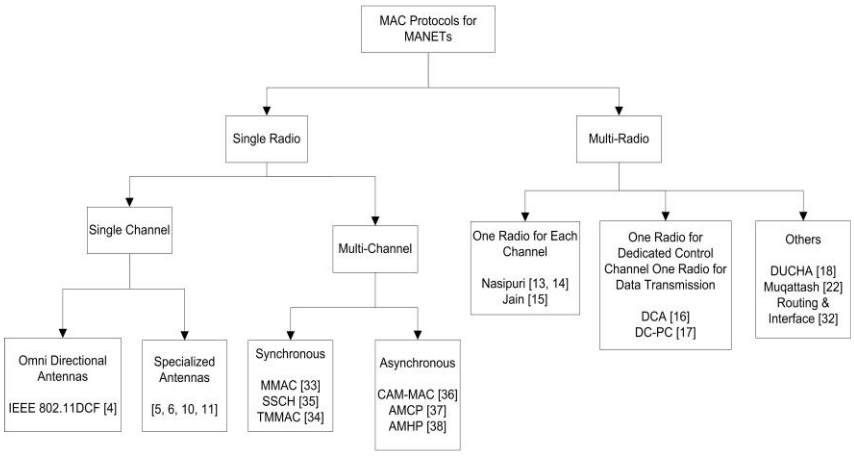

Fig. 1. Classification of MAC Protocols

II. SINGLE-RADIO SINGLE-CHANNEL MAC PROTOCOLS

The earliest MAC solutions for MANETs are mostly single-radio per node, operating on a single channel. Both the control and data packets along with control messages needed for coordination of data transfer between nodes are all transmitted and received on the same channel. The reason for using a single channel, mostly, if not completely depends on the inability of wireless interface devices to operate in full duplex mode on preferably many different channels, simultaneously. Present day wireless interface cards are half duplex and can only transmit or receive data at any given time. The most widely used and implemented single-radio, single channel MAC protocol for MANETs is the IEEE 802.11DCF [4]. Originally designed for wireless local area networks (WLANs), it can also used in ad hoc mode. Nodes running IEEE 802.11 DCF exchange RTS/CTS messages to reserve medium for data transmission. A node that has data packets pending for transmission to a destination node issues an RTS message. When the receiver receives the RTS message, it issues a CTS message in reply. Both the sender and receiver specify in their RTS/CTS, the time duration for which the channel will be used. To keep track of the channel usage nodes maintain a variable called *Network Allocation Vector* (NAV) which contains the time duration for which the channel will remain busy. This process is known as *Virtual Channel Sensing* and is designed to restrict the surrounding nodes from using the channel during the specified time interval. The use of RTS/CTS exchange eliminates the hidden terminal problem in wireless networks. If a node has data packets to send to a destination, it first senses the channel. If the channel is idle, an RTS message is issued. In case the channel is busy, the node uses a random *backoff* counter, the value of which is no greater than the *contention window* (CW). Every node in the network maintains the CW variable which is the contention window size. Whenever a node joins the network for the first time or, after each successful data transmission, the value of CW is set to CWmin. After choosing the *backoff* counter value, the node waits for the channel to become idle. When the channel becomes idle, the node starts decrementing the backoff counter by one after each time slot as long as the channel remains idle. If the channel becomes busy, the node freezes the counter and starts to wait for the channel to become idle once again. When the channel becomes idle and the counter value has been decremented to zero, the node will send an RTS message to the intended target and try to reserve the channel. There is room for collision between two RTS messages when two nodes choose the same *backoff* counters. The probability of that occurring depends on the number of nodes in the network. Greater the number of nodes in the network, the greater will be the chance of collision. If a collision occurs, nodes will double the size of its contention window. Four different interframe spacings are used before a node transmits a packet. This enables different packets to have different priorities when contending for the channel. The four different interframe spacings in order of increasing length are SIFS, PIFS, DIFS and EIFS. An ACK packet is sent after SIFS whereas a data packet is sent after DIFS, thus giving ACK packets priority over data packets. IEEE 802.11 DCF is a contention based protocol and to avoid collision, RTS/CTS messages are exchanged. It uses CSMA/CA while exchanging these packets. IEEE 802.11 DCF does not rely on any specialized antennas at the physical data transmission layer. In other words, the communication is omni-directional in nature.

Efforts have been made in [5] to enhance the performance of IEEE 802.11 DCF with directional antennas. With omni-directional antennas, a node running the IEEE 80.11 cannot transmit data if it is not receiving any data, *i.e.* if an idle node wants to transmit data and there is active transmission in the neighborhood then all a node can do is to wait for the channel to become idle before it can transmit data. The contribution made by [5] is to add receiver location information to the MAC sub-layer. By doing so, a node in the idle state that wants to transmit data, can beamform its transmission in the direction of the receiver without disrupting communication in its neighborhood. The prerequisite for such an arrangement is that the intended receiver must be outside the communication range of the neighborhood of the sender. The second notable change this scheme does to the traditional IEEE 802. 11 DCF is the way nodes access their MAC data queue and select packets for transmission. In the original DCF protocol, data packets are selected for transmission on the first come first serve basis. But since this enhanced DCF MAC protocol must select a destination node that resides outside the current communication range of the neighborhood of the sender, the sender is forced to alter this scheme and select a destination node that is appropriate for beamforming. A similar approach based on directional antennas to improve quality of service (QoS) is used by Tomas Cakan and Vladimir Wieser in [6].

The most prominent advantages beamforming antennas can provide are reduced interference between simultaneous transmissions, increased throughput capacity by opportunistic transmission, security, QoS and efficient power consumption. Beamforming antennas have been successfully deployed in cellular networks in the past [7], [8]. Smart *sectorised* antennas have been used to extend the range and throughput in WLANs in [9]. Beamforming antenna technology has been proposed for MANETs to increase throughput capacity in [10], [11]. It is a vast area of research and a large number of protocols have been proposed in the past in this area. A more detailed survey on MAC protocols for MANETs based on the beamforming antenna technology can be found in [12]. Taxonomy on MAC protocols is presented in Table I.

TABLE I: TAXONOMY OF MAC PROTOCOLS

Protocol	Synchronization	Channel Assignment	Multiple Radios	Multi-Channel	Specialized/Directional Antenna	Power Control
802.11 DCF	Not Required	-	No	No	No	No
MMAC	Required	Dynamic	No	Yes	No	No
SSCH	Required	Scheduled/ Dynamic	No	Yes	No	No
[1]	Not Required	-	No	No	Yes	No
[54]	Required	Distributed/Dynamic	Yes	Yes	No	Yes
CAM-MAC	Not Required	Dynamic	No	Yes	No	No
AMCP	Not Required	Dynamic	No	Yes	No	No
TMMAC	Required	Dynamic	No	Yes	No	No
DCA	Not Required	Dynamic	Yes	Yes	No	No
DCA-PC	Not Required	Dynamic	Yes	Yes	No	Yes
DUCHA	Required	Static	Yes	Yes (one control and one data channel)	No	No
AMHP	Not Required	Scheduled/ Dynamic	No	Yes	No	No
[25]	Not Required	Dynamic	Yes (one radio for each channel)	Yes	No	No
[26]	Not Required	Dynamic	Yes (one radio for each channel	Yes	No	No*
[27]	Not Required	Dynamic	Yes (one radio for each channel	Yes	No	No*

*By power control we mean that nodes in the network are capable of adjusting their transmit power while transmitting data to a certain destination. It does not include power sensing on the received signal.

III. MULTI-RADIO MAC PROTOCOLS

Multi-radio MAC protocols have been proposed for MANETs in order to enhance the throughput capacity of such networks. Almost all of the multi-radio MAC solutions proposed in the past, use multi-channel mode of communication. Some of the early works in multi-radio MAC protocols for MANETs used two or more radios. The protocols proposed by Nasipuri *et al.* use a separate radio device for each channel in the network [13], [14]. The work of Jain *et al.* in [15] also calls for a separate radio device for each channel in network. Although having a separate radio device for each channel in the network or at least in the neighborhood of a node can greatly improve network throughput and greatly reduces the chances of collisions, it is however, an impractical solution for MANETs for two obvious reasons. The first one is that most PDA's or laptop computers available in the market that can be used as nodes in MANETs come equipped with only one radio interface. Secondly, operating more than one radio device has a high energy cost associated with it and MANET devices cannot afford such high energy consumption cost.

Wu *et al.* proposed DCA [16] and DCA-PC [17] protocols that requires two radio interfaces for each node in the network. Both these protocols use one radio interface for a dedicated control channel whereas the bandwidth on the other radio device is divided into multiple channels for data exchange. The radio interface used in DCA for data exchange has multiple data channels with equal bandwidth. Nodes negotiate a new data channel on the control channel and switch to the data channel to exchange data. Each node maintains a *Channel Usage List* (CUL) that keeps track of channel usage information and a *Free Channel List* (FCL) which contains information about free channels. If a source node wants to communicate with a destination, the source will send its FCL in an RTS message to the destination node. The destination node will then compare the source nodes' FCL to its CUL and choose a free data channel. The destination node will send an acknowledging CTS with the selected data channel to the source. The source node will send a *RES* message to the destination for final confirmation that the channel has been reserved and to ensure that other nodes refrain from using this channel. Both the source and destination will switch to the selected data channel and start exchanging data. In DCA-PC, before transmitting data, nodes consider the interference level on channels before selecting a data channel. A channel with the lowest interference level is selected for data exchange. Nodes also adjust their power levels before transmitting their data based on appropriate power level required for each destination node. Zhai and Wang proposed DUCHA, a dual channel MAC protocol for multi-hop ad hoc networks in [18]. DUCHA uses an out of band busy tone and two channels for communication. One channel is used for exchanging control information and the other one is used for exchanging data.

There have been proposals of specialized transceivers that can send and receive data on multiple channels simultaneously in [19], [20]. This would solve a number of potential issues such as the multi-channel hidden terminal and the deafness issue in MANETs [21] but generally, present day MANET devices available in the market are mostly equipped with a single radio device that can only transmit or receiver data at any given time.

The protocol proposed by Alaa Muqattash and Marwan Krunz in [22], uses two radio transceivers and additional carrier-sense hardware for sensing the control channel. It is a CDMA based protocol that uses the channel gain information obtained through the out-of-band channel sensing device to limit its transmission power to the vicinity of the intended receiver. This feature of controlled power allows simultaneous multiple transmissions in a neighborhood.

CDMA uses spread spectrum (SS) communication technique on the physical layer. With the SS approach, all the nodes in a neighborhood share the entire spectrum allocated for communication. Simultaneous multiple transmission are made possible by using a code called Pseudo Random Noise or PN code. If each node uses a distinct PN code, all the nodes in a neighborhood can simultaneously transmit data without causing any interference and can be received at the corresponding receivers using the same unique PN code. The original message sent by the sender can be extracted from the composite signal received at the receiver using mathematical calculations specific to CDMA systems. IEEE 802.11 DCF uses SS but only to remedy the harsh wireless medium as the error rate on SS is very low compared to some of the other traditional modulation techniques. IEEE 802.11 uses the same PN code at each node thus limiting transmission to a single transmitter at any given time.

CDMA based MAC protocols [23]-[26] are ideal for MANETs in terms of throughput, but there are certain limitations to its deployment in MANETs. The most obvious one is that CDMA technique, like the TDMA, was designed for cellular systems with centralized control such as base stations. For simultaneous undisruptive communication, each node must have a unique PN code. Since cellular networks are centralized, PN code assignment in such networks is not an issue but there is no infrastructure support in MANETs and hence PN code assignment is a major hurdle for CDMA based MANETs [27], [28]. A majority of CDMA based MAC protocols for multi-hop wireless networks assign codes based on a node's neighborhood [29] in a distributed fashion. The focus is to assign codes to nodes that are unique in their neighborhood. Another issue in CDMA for MANETs is the use of spreading code protocol to assign codes for packet transmission and listening to the wireless medium for receiving data [30]. There can be three different types for such a protocol, a receiver based, transmitter based and a hybrid scheme involving both the receiver and the transmitter.

Wang *et al.* proposed a multi-channel MAC protocol for MANET's based on busy tone with channel width adaptation technique [31]. Each node is equipped with two interfaces, a busy tone interface and a data interface. The busy tone channel is used to avoid the multi-channel hidden terminal problem and to deal with the deafness issue [21]. The channel width adaptation technique used in this protocol allows a single data channel to be divided into multiple sub-channels which can further improve the performance of the protocol. Several sub-channels can be integrated into a single data channel which makes this protocol more flexible in adopting to different bandwidth needs from time to time during the course of the network operations.

The protocol proposed in [32] deals with MAC in conjunction with routing. It is a multi-radio multi-channel MAC protocol. They argue and propose a channel assignment strategy for different interfaces that will allow multi-channel communication using existing IEEE 802.11 based NIC devices. The proposed interface assignment strategy allows nodes to have less number of interfaces mounted on each node compared to the number of channels used. They have called for a specialized routing protocol that can compute the total cost of a route as the weighted combination of the switching cost, the diversity cost, and the global resource usage cost.

IV. Single-Radio Multi-Channel MAC Protocols

The Multi Channel MAC (MMAC) protocol [33] is a multi-channel MAC solution that requires one radio device per node. MMAC is not an asynchronous protocol which means that nodes in the network require network wide clock synchronization. In MMAC, time is divided into beacon intervals of 100 ms. These beacon intervals are further subdivided into a 20 ms *ATIM* (Ad Hoc Traffic Indication Message) window and a data window. During the *ATIM* window, nodes negotiate a new data channel and then switch to the data channel for actual data exchange. *ATIM* is a term borrowed from the original IEEE 802.11 Power Saving scheme. A data structure called *Preferable Channel List* (PCL) is maintained by each node in the network. The PCL data structure contains channel usage information of the surrounding nodes. Three different preference levels are assigned to the channels namely, *high, medium* and *low*. *High* preference means that the channel is currently in use for the duration of the current beacon interval. *Medium* preference means that the channel is free to be used if a node wants to use it. *Low* preference means that one or more neighboring nodes are currently using the channel and hence is not available for use. Load balancing between channels is achieved by maintaining a per channel counter to record the channel usage in a beacon interval. The hosts switch to the base channel for exchanging *ATIM* messages for channel negotiation and reservation but the same base channel can also be used for data exchange outside of *ATIM* window. When a sender wants to transmit data to a destination node, it inserts its PCL list into the *ATIM* frame and sends it to the destination node. If the destination node can find a free channel from the senders PCL list, it will reply with an *ATIM-ACK* frame. If the source and destination cannot find a free channel, they will wait for the next beacon interval. In the next beacon interval, if they find a free channel, source node will send an *ATIM-res* frame and the two nodes can start exchanging data on the selected channel. MMAC achieves better throughput than DCA using a single radio interface [33]. The significant overhead that MMAC adds to the network is the bandwidth consumed to achieve clock synchronization between nodes and the fixed *ATIM* window size for channel reservation. If there are not enough channel reservation messages exchanged by the nodes to consume the entire 20*ms ATIM* window, the remaining time is wasted because nodes that have already finished exchanging channel negotiation messages must wait for the data window to begin actual transfer of data on selected channels. A dynamic *ATIM* window size would resolve this wastage by dynamically adjusting the size of ATIM window during each cycle as proposed in [34] The Slotted Seeded Channel Hopping protocol (SSCH) [35] also requires one radio device for each node. SSCH requires clock synchronization among nodes. The radio interface in SSCH hops between orthogonal data channels based on a predefined set of rules. Nodes maintain a channel schedule that will be used in the subsequent slots. The channel schedule is a compact representation of a current channel and a set of rules for updating the channel. The rules are represented as a set of 4 (Channel, Seed) pairs. Each node iterates through its set of 4 (Channel, Seed) pairs in each slot and performs the following channel update.

$$CH(X) \leftarrow (CH(X) + Seed(X)) \bmod (N)$$

where X is from 0 to 3 and N is the number of channels. Every node frequently broadcasts its channel schedule and also keeps track of other nodes' channel schedule. When a source node wants to exchange data with a destination, the source will follow the channel schedule of that particular destination to initiate data communication.

In CAM-MAC [36], node cooperation has been introduced into the frame work of multi-channel MAC protocols. CAM-MAC is a single radio, asynchronous multi-channel MAC protocol hence no clock synchronization techniques are needed. When a node wants to communicate with another node, it broadcasts a probe message called *PRA* (Probe-A) which contains the channel index selected by the source node based on its own knowledge of the surrounding. The surrounding nodes overhearing this transmission, if feel that collision maybe possible on this channel, they will issue a *INVs* (Invalid) message to indicate to the sender that the channel is not safe for transmission. If the source node does not receive any *INVs* after SIFS (Short Inter Frame Space), the destination node issues a *PRB* (Probe-B) which replicates the channel index from *PRA* sent initially by the source. The neighboring nodes of the node receiving *PRB* also perform validations on *PRB* and may issue *INVs* as explained above. In case the source node does not receive any *INVs*, it will issue a confirm message *CFA* (Confirm-A) and the receiver will reply with *CFB* (Confirm-B). Afterwards, both nodes switch to the agreed upon channel and start exchanging data.

Asynchronous Multi-Channel Coordination Protocol (AMCP) [37] is also is an asynchronous multi-channel MAC protocol. There is one dedicated control channel in AMCP and N data channels. If a node A wants to communicate with node B, A will select a random data channel or the channel indicated by a variable called *prefers* and insert it into the RTS message and send to node B. If the requested channel is not available at B, node B will send a rejecting CTS to node A. Node B will reply with a confirming CTS if the indicated channel is available at B. Upon receiving the CTS message, both nodes will switch to the selected channel and exchange a data packet. After the exchange, both nodes will switch back to the control channel and contend for either the same channel used in the previous exchange or wait for the timers to expire on other channels and then contend for a new data channel.

TMMAC proposed by Zhang *et al.* in [34], is a TDMA based multi-channel MAC protocol for MANETs. TMMAC requires network wide clock synchronization between nodes for its successful operation. In TMMAC, time is divided into fixed beacon intervals. Each beacon interval is divided into an ATIM window and a data communication window. Channel negotiations take place during ATIM window whereas in data communication window, the actual transfer of data takes place. TMMAC is somewhat similar to MMAC, the only difference between the two approaches is that the *ATIM* window is dynamically adjusted in TMMAC and the data communication window is further divided into time slots. During the *ATIM* window, the sender and receiver decide on which channels to use and also specify the time slots to be used for a specified number of packets. Each time slot is long enough to accommodate the transmission of a single data packet including acknowledgement and time needed for switching between channels. Both the sender and receiver switch to the agreed upon channel in the specified time slot to exchange a data packet.

Long le proposed Asynchronous Multi-channel Hopping Protocol (AMHP) in [38]. It does not require clock synchronization between nodes. Each node running AMHP chooses a home channel based on its MAC address. Each node has a set of channels called *rendezvous channels.* These channels are used when two nodes cannot find each other on their respective home channels. The protocol is designed with a per- connection based communication rather than per-packet based communication. Nodes tend to transmit and receive multiple packets after each channel reservation and negotiation process. This approach is helpful in reducing frequent channel switching.

Several multi-channel MAC protocols with a single radio device on each node have been proposed for wireless sensor networks (WSNs). Some of these WSN protocols can also be utilized for MANETs with slight adjustments [39], [40]. Y-MAC [39] proposed by Kim *et al.* uses a base channel for channel negotiations and data communication during normal traffic loads but when the traffic load increases beyond a predefined threshold, nodes start to migrate to other channels. Y-MAC is a TDMA based protocol and nodes in the network are kept synchronized by a sink that periodically broadcasts time reference to neighboring nodes. Each node selects a channel hopping schedule and periodically broadcasts it. Nodes also keep track of the channel hopping schedule of neighboring nodes and use it whenever there is a need for communication with that particular node. The MAC protocol proposed in [40] uses a similar technique for assessing the condition of the base as the one used in [39] but a clustering technique is used for channel assignment. Using this approach, each node is assigned a home channel. Each node receives a tuple <s,f> from its neighboring nodes. Where s is the total number of successful attempts of acquiring the channel and f is the number of unsuccessful attempts at acquiring the channel. Nodes periodically exchange these tuples to compute the probability of successfully acquiring the channel. If the probability of acquiring the channel is too low then nodes interpret this as a congested base channel and nodes consider switching to other channels.

There is a class of MAC protocols that uses a hybrid mix of TDMA, FDMA or CDMA to gain access to the wireless medium [1]-[3]. In HyMAC [1], the authors proposed a hybrid scheme of TDMA and FDMA. Each TDMA cycle consists of a number of frames and each frame is divided into a number of time slots. Each time slot is long enough to transmit a maximum size data packet. Some slots in a frame are contention based whereas some are scheduled. A base station is responsible for assigning a frequency channel and specific time slots to each node. The problems with such a scheme to be deployed in a MANET environment are that they require an out-of-band synchronization scheme. Another big issue of concern is that MANETs don't have base stations. For this scheme to be implemented in MANETs environment, a distributed channel assignment scheme would be required and synchronization should be achieved using a single radio interface without the help of out-of-band equipment. The protocol in [3], RSQ-MAC, propose a hybrid TDMA/OFDMA MAC solution for *tactical* MANETs. This scheme doesn't require infrastructure support as it is intended for use in MANETs. In RSQ-MAC time is divided into frames and each frame has multiple transmission slots. Channels are further subdivided into multiple OFDM subcarriers. An algorithm called *operational phase* is used to assign selected slots and subcarriers to each node for data transmission.

V. Discussion and Conclusion

In this paper we have discussed various methods and techniques used so far in the design and development of

MAC protocols for MANETs. We also looked into a few protocols developed for WSNs that can be deployed in a MANET environment with minor adjustments. Some of the techniques proposed call for interaction between different layers of the protocol stack such as, a MAC solution that works in conjunction with routing. The traditional layered architecture for network communication is rigid [3], [41]-[45] and thus limits the ability of nodes to select better routes. We believe that a MAC solution that interacts with the physical layer and network layer (routing) would provide better results compared to a strict layered approach [46].

We also looked into antenna technologies used in MANETs especially the directional or the beamforming antennas. In communication environments where a single radio interface is using a single channel, only one device can transmit whereas the rest of the nodes in its transmission range either receive the data being transmitted or waits for the transmission to end before they can transmit their own data. These enhanced antenna based MAC solutions can achieve better throughput performance by opportunistic transmission without affecting other transmissions in their neighborhood. Specialized antennas based MAC solutions also fall under the paradigm of cross-layer design because beamforming antennas needs instruction from the MAC layer before directing their transmission at particular node or group of nodes.

Multi-radio MAC solutions hold great promise in enhancing network capacity. The limiting factors against the use of multi-radio MAC protocols is their high energy consumption and the fact that most off-the-shelf MANET devices are equipped with a single radio interface.

Single-radio multi-channel MAC solutions are more realistic and desired for use in MANET environments. Such solutions can further be subcategorized into synchronous and asynchronous multi-channel MAC solutions. MAC protocols that require fine grained clock synchronization techniques are expensive both in terms of bandwidth consumption and implementation but also impact the scalability of MANETs. Out-of-band synchronization techniques such as GPS are costly since GPS is not a free service. Besides, GPS based solutions work well in outdoor scenarios as GPS devices need a clear line-of-sight with the satellites in orbit. Another problem with using GPS for synchronization is its timing accuracy. A standard GPS service provides a timing accuracy of about 100*ms* which is too large for MAC protocols. Clock synchronization techniques that use an additional radio interface can solve the problems related to GPS based solutions but such a solution will make it a multi-radio solution hence it will bring back the problems of multi-radio based MAC protocols into the fore. An alternate solution to the out-of-band clock synchronization techniques is the use of software-based clock synchronization techniques [47]-[49]. Such solutions are difficult to implement and networks that use software-based synchronization techniques do not scale well [47]. Moreover, most of the synchronization methods involve broadcasting timing information to a segment or entire network by one or many nodes. The issue with broadcasts in MANETs involving multiple broadcasting nodes is that they are not protected by RTS/CTS exchange and thus are susceptible to collisions. The problem becomes worse in heavy traffic conditions or densely populated networks.

Another interesting observation that comes to light regarding multi-channel MAC protocols is the number of channels used. Frequency as we know is a precious and scarce resource [50]-[53]. Ubiquitous high data-rate networks of the future will cover large areas and will require more frequency resources. In the near future, MAC protocols that take frequency reuse more seriously would be more desirable and practical solutions compared to the protocols that do not take frequency reuse into consideration.

Channel switching delay is another area of concern while designing single-radio multi-channel MAC protocols. Some of the single-radio multi-channel MAC protocols proposed in the past assume a far lower channel switching delay than what the present day off-the-shelf wireless NIC devices are capable of [54]. Multi-channel MAC solutions such as MMAC [33] and AMCP [37] assume a channel switching delay of 224 μs, while SSCH [35] has assumed the delay to be 80 μs. Practical experiments carried out by Long Le in [54] on off-the-shelf IEEE 802.11 based NIC devices reveal that the channel switching latency is between 4 and 6*ms* and in some cases, even greater than 6*ms*.

Most of the constraints on the design of multi-channel MAC protocols for MANETs stem from the inherent inability of the wireless NIC devices available in the market to send and receive data simultaneously on multiple channels. An ideal MAC solution for MANETs would be one that is able to operate on different frequency channels without having the need to perform channel switching. Perhaps in the not so distant future, such devices will be made available to commercial use at low cost, but as of now, researches will have to continue finding an optimum solution within these constraints.

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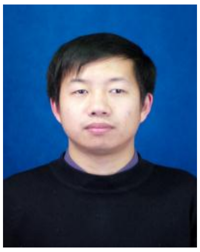
Amjad Ali is a PhD student at Harbin Engineering University. He received his BS degree in computer science from University of Peshawar in 2001. He received his MS degree in computer science from Agricultural University Peshawar in 2004. He has also received MS degree in computer based communication networks from Institute of Management Sciences, Hayatabad, Pakistan, in 2008. He is the author of several research papers. His research interests include routing in mobile ad hoc networks, cognitive networks and multi-channel MAC protocols for wireless networks.

Wang Huiqiang received MS degree in information and computing sciences from Harbin Engineering University in 1985. He received PhD degree in computer application technology from the department of computer science and technology, Harbin Engineering University in 2005. He is currently a lecture in Harbin Engineering University. His research interests are in the areas of network technology and information security, trusted computing, autonomic computing and cognitive network.



Hongwu Lv received the MS degree in information and computing science from Harbin Engineering University in 2006, and the PhD degree in computer application technology from the department of Computer science and technology, Harbin Engineering University in 2011. He is currently a lecture in Harbin Engineering University. His research interests are in the areas of performance evaluation and autonomic computing.

Chen Xiaoming received MS degree in computer application technology from the department of computer science and technology, Harbin Engineering University in 2010. She is currently a doctoral candidate at Harbin Engineering University. Her research interests are in the areas of cognitive networks, cross-layer design and network architecture.