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An Energy Efficient Multichannel MAC Protocol for QoS Provisioning in MANETs

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Abstract

This paper proposes a TDMA-based multichannel medium access control (MAC) protocol for QoS provisioning in mobile ad hoc networks (MANETs) that enables nodes to transmit their packets in distributed channels. The IEEE 802.11 standard supports multichannel operation at the physical (PHY) layer but its MAC protocol is designed only for a single channel. The single channel MAC protocol does not work well in multichannel environment because of the multichannel hidden terminal problem. Our proposed protocol enables nodes to utilize multiple channels by switching channels dynamically, thus increasing network throughput. Although each node of this protocol is equipped with only a single transceiver but it solves the multichannel hidden terminal problem using temporal synchronization. The proposed energy efficient multichannel MAC (EM-MAC) protocol takes the advantage of both multiple channels and TDMA, and achieves aggressive power savings by allowing nodes that are not involved in communications to go into power saving “sleep mode”. We consider the problem of providing QoS guarantee to nodes as well as to maintain the most efficient use of scarce bandwidth resources. Our scheme improves network throughput and lifetime significantly, especially when the network is highly congested. The simulation results show that our proposed scheme successfully exploits multiple channels and significantly improves network performance by providing QoS guarantee in MANETs.

Keywords: Multichannel MAC, MANETs, frequency spectrum, TDMA, hidden terminal, energy efficiency, IEEE 802.11

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1. Introduction

In recent years, much interest has been given in the design of wireless networks for local area communications. A key problem of wireless networks is medium access control (MAC) protocol, which deals with efficient resource sharing for multiple nodes during communications [1]. A MAC protocol addresses how to resolve potential contentions and collisions when using the communications medium. Many MAC protocols have been proposed for wireless networks [2][3][4][5][6][7][8][9]. The IEEE 802.11 standard [10] for wireless local area network makes multiple channels available for use.

By exploiting multiple channels, we can achieve higher throughput compared with single channel communications, since the use of multiple channel can reduce the interference influence [11]. It is not an easy problem to design a MAC protocol to exploit multiple channels, because each of the IEEE 802.11 devices is equipped with a single half-duplex transceiver. Though the transceiver can switch different channels dynamically, but because of the half duplex nature it can only transmit or receive on one channel at a time. Thus, when a node is receiving on a particular channel, it will not be able to hear other nodes' communications on a different channel at the same time. Due to this, a new type of hidden terminal problem occurs in this multichannel environment, which is referred to as multichannel hidden terminal problem. We discuss the solution of this problem in more detail in Section 4.1.

Because of the multichannel hidden terminal problem [12], a single channel MAC protocol does not work well in a multichannel environment. To achieve high throughput with congested traffic, the design of multichannel MAC protocol is a good solution. In multichannel MAC protocol all the active nodes select their data channel on a default channel during control phase and then transmit their data packets on the selected channel during data communications phase. One of the important design issues of MAC protocol is how to utilize radio spectrum efficiently to resolve potential contentions and collisions among mobile nodes.

In ad hoc networks consisting of portable devices (at least in part), energy management is of prime importance because of the limited energy availability in the portable devices. With the increase in the number of mobile devices, and with communications being the major cause of energy consumption, the power savings of a MAC protocol become a pertinent issue [13]. Therefore, it is desirable to build a network protocol that maximizes the time a device is in sleep mode, and also maximizes the number of wireless devices that can be in sleep mode.

In wireless networks, bandwidth is a scarce resource that can be shared either dynamically or deterministically. Providing quality of service (QoS) is more difficult in MANETs due to a number of reasons: (1) because of the broadcast nature of the wireless transceiver the bandwidth of each link will be affected by the transmitting/receiving activities of its neighboring links, (2) in ad hoc networks, QoS guarantee needed for multi-hop communications, and (3) because of the dynamic network topology nodes may join, leave, and rejoin at any time and anywhere, as a result, existing links may disappear, and new links may be formed in a time varying manner.

We use bandwidth as a main QoS parameter in this paper. This is because the bandwidth guarantee is one of the most critical requirements for real-time applications. For bandwidth reservation, TDMA scheme is generally used in wireless networks. "Bandwidth" in time-slotted network can be defined as the number of "free" timeslots. Accordingly, link bandwidth is the number of common free timeslots between two nodes and path bandwidth of the two nodes is the set of free timeslots available between them. If the two nodes are adjacent, the path bandwidth is the link bandwidth. In general, calculating available bandwidth of a path in a MANET, based on slotted-scheme, not only needs information about the available bandwidth on the links along the path, but also needs to know how to allocate the free timeslots. Therefore, computing available bandwidth in MANETs is difficult and is actually NP-complete. If the bandwidth requirement B of a connection is larger than 1, we need to allocate each link B timeslots in one frame.

In this paper, we propose an energy efficient multichannel MAC protocol for QoS provisioning, which enables nodes to dynamically select not only channels but also timeslots, such that multiple communications can take place in the same region simultaneously, each in different channel. We consider a MANET that does not rely on infrastructure, so there is no central authority to perform channel management. The main idea is to divide system time into fixed-time beacon intervals, and have a small window at the start of each interval to indicate traffic and select channels and timeslots for use during the interval. Apart from the nodes that will be involved in data transmissions, all other nodes turn into sleep mode in the rest of the beacon interval. The proposed scheme can eliminate contention between nodes, decompose contending traffics over different channels and timeslots based on actual traffic demand, which guarantees QoS in MANETs. The main contributions of this work can be summarized as follows:

- We present an energy efficient multi-channel MAC protocol called EM-MAC, which not only utilizes the bandwidth more efficiently, but also achieves more aggressive power savings that prolongs system lifetime.
- EM-MAC achieves higher channel utilization. Furthermore, the control packets collisions will decrease by distributing the source and destination pair to compete for the data channel.
- Although EM-MAC uses single transceiver at each node but solves the multichannel hidden terminal problem using temporal synchronization.
- We provide an analytical model for EM-MAC that accurately characterizes the performance of EM-MAC and is validated through simulations.
- EM-MAC provides QoS guarantee based on actual traffic demand. Furthermore, EM-MAC supports broadcast efficiently.
- EM-MAC achieves higher throughput and lower end-to-end delay by reducing collisions and contentions between nodes and by utilizing the multiple channels efficiently.

The rest of the paper is organized as follows. Section 2 describes the related work. The system model is presented in section 3. The design and operation of the proposed protocol are illustrated in section 4. Section 5 presents the analytical model. We present the performance evaluation in section 6, and finally in section 7 we conclude the paper.

2. Related Work

A large number of multichannel MAC protocols and TDMA scheduling algorithms have been proposed in the literature. Many multichannel MAC protocols are based on special hardware requirements. In our proposed EM-MAC protocol, we do not require any special hardware but only a single half-duplex radio transceiver. Multichannel MAC protocols that are closely related to the EM-MAC protocol are the ones that extend IEEE 802.11 DCF [10] and use certain kinds of control message for channel selection. Typical protocols in this group are multichannel MAC (MMAC) [12], local coordination-based multichannel MAC (LCM MAC) [14], cooperative asynchronous multichannel MAC (CAM-MAC) [15], TDMA based multichannel MAC (TMMAC) [16], and multichannel MAC with channel distribution (CD-MAC) [17].

MMAC [12] assumes *C* channels are available for use. Each node maintains a data structure called the preferable channel list (PCL) which records the usage of channels inside the transmission range of the node. PCL also indicates which channel is preferable for the node to use. Based on this information, the channels are categorized into three states: high preference, medium preference, and low preference. During the ad hoc traffic indication messages (ATIM) window, every node must listen to the default channel for periodic beaconing and to transmit ATIM packets. MMAC assumes networks are time-synchronized and system time is divided into fixed-length beacon intervals. Each beacon interval consists of a fixed-length ATIM window, followed by a communication window. During the ATIM window, every node listens to the same default channel to decide which channel to use for data communications. After the ATIM window, nodes that have successfully decided channels send data packets using 802.11 DCF to avoid congestion. Nodes that do not achieve successful negotiations or do not have packets to send or receive go into sleep mode to save power. Since the MMAC protocol uses global synchronization, it avoids the multiple channel hidden terminal and missing receiver problems. However, it inherits all the problems of a scheduled access with a synchronized control and data frame structure. Its performance can be obviously degraded because of the random channel selection. Furthermore, MMAC protocol leads the problem of wasting multiple channels bandwidth greatly.

Two new MAC protocols for multichannel operation in wireless ad hoc and mesh networks have been proposed in [14]. The first protocol, extended receiver directed transmission protocol (xRDT), is based on the receiver directed transmission (RDT), a multichannel solution, which uses a notion of quiescent channel. xRDT solves the problems faced by RDT, such as multichannel hidden terminal and deafness, by using an additional busy tone interface and few additional protocol operations. A novel single interface solution, called local coordination-based multichannel MAC (LCM MAC) is also developed. LCM MAC performs coordinated channel selection and channel switching to provide multichannel support. However, some important issues like the effects of mobility and broadcasts mechanism are not discussed in these protocols. Furthermore, energy efficiency and QoS guarantee are also not addressed.

In many of the MAC protocols in the literature, nodes make independent decisions for transmitting a packet and to backoff from transmission. Node cooperation into MAC protocol is introduced in CAM-MAC [15]. They study the design of cooperative MAC protocols in multichannel environment where each node is equipped with a single transceiver. To select a free channel to use, nodes cooperate by helping each other. This simple idea of cooperation has several qualitative and quantitative advantages. The cooperative asynchronous multichannel MAC protocol (CAM-MAC) is extremely simple to implement and is naturally asynchronous. However, this work does not address the problem of energy efficiency and providing QoS guarantee that are considered in our work.

An energy efficient multichannel MAC protocol, called TMMAC is proposed in [16]. In TMMAC, system time is divided into fixed periods, which consists of an ATIM window followed by a communication window. The ATIM window size is dynamically adjusted based on different traffic patterns to achieve higher throughput and lower energy consumption. The communication window is time-slotted. During the ATIM window, each node decides not only which channels to use, but also which timeslots to use for data communications. Then each node adopts the selected channel for each timeslot to transmit or receive data packets. From the point of view of TDMA, TMMAC is an energy efficient and a traffic-adaptive scheduling algorithm. However, this protocol does not address the problem of providing QoS guarantee that is considered in our work.

A multichannel MAC protocol for MANET that enables nodes to transmit packets in distributed channels is proposed in [17]. In this protocol, the ATIM window is divided into two windows: the deciding channel window (DCW), and the exchanging packet window (EPW). Source and destination nodes can negotiate with each other in deciding a channel that can be used to compete for the final data channel in the DCW. In the EPW, source and destination nodes can compete to obtain a channel to transmit packets. This mechanism can distribute pair source and destination nodes to compete for a data channel. Hence, because of this, collisions can be avoided greatly and throughput can be increased. Our work is different from them, we consider TDMA-based slotted scheme in communication window instead of contention-based scheme.

A cross-layer design for a reliable video transmission over wireless ad hoc networks based on multichannel MAC protocol is presented in [18]. The lack of consideration for time-bound applications and for cross-layer strategy makes the existing works unrealistic to be adopted for video streaming over MANETs. Therefore, there is a pressing need to design a cross-layer approach that is suitable for time-bound applications in video streaming by taking full advantages multichannel MAC protocols. They use maximum latency rate (MLR) as the channel quality metric. Furthermore, MAC utilization and queue length of MAC layer are used to improve the congestion-aware routing protocols with AODV and DSR. However, this work does not address the problem of energy efficiency that is considered in our work.

An efficient multi-channel MAC protocol, named MAXM, for ad hoc networks is proposed in [19]. MAXM is a scheduled-access protocol, which can be implemented easily. The idea of MAXM is to maximize utilization of bandwidth by adopting a distributed self-stabilizing maximal matching-transmission algorithm. They prove that given a fixed number, p, of packets, MAXM is able to guarantee that all packets are delivered within $O(pN + pT)$ time in the network of N mobile hosts, where T is the time to transmit a packet on a non-conflicting channel. MAXM uses IDLETONE scheme to distinguish idle nodes and BANTIME scheme to avoid waiting for busy destinations. Our work is different from them; we use TDMA-based scheduled channel access and ATIM for indicating the traffic and to select channel-timeslots.

A multi-channel MAC protocol for single-hop scenario is presented in [20]. An analytical model is proposed to calculate the network throughput that are designed to schedule multiple packets to be transmitted on different data channels simultaneously, having a dedicated control channel. Based on the analytical model, a scheme by tuning the initial contention window size is proposed to maximize the network throughput. The proposed scheme can find an optimum initial window size to maximize the total network throughput. The proposed protocol allows better channel utilization by reducing the number and the size of control packets. Though this protocol performs better in dedicated control channel protocols for single-hop scenario but it does not investigate the performance in multi-hop cases.

An asynchronous multichannel hopping protocol (AMHP), a multi-channel MAC protocol that does not build on the impractical assumptions: low channel switching latency and fine-grained clock synchronization has been proposed in [21]. AMHP has two attractive features: it does not require clock synchronization among nodes and it amortizes the channel switching overhead by avoiding frequent channel switching. However, this protocol does not consider the energy efficiency and the QoS guarantee that are addressed in our protocol.

3. System Model

We consider a multi-hop MANET, where no central entity exists to coordinate medium access and channel allocation. Each node is equipped with a single half-duplex transceiver. The spectrum bandwidth is divided into multiple orthogonal channels. Consider the spectrum consisting of C non-overlapping channels, each with bandwidth B_c (c = 0, 1, 2, …, C-1). A transceiver can be tuned to different channels, but can only use one channel at a time.

We assume that each transceiver always transmits at a fixed transmission power and hence, their transmission range R_c and interference range I_c, which is typically 2 to 3 times of transmission range [11], are fixed for a particular channel c. We use a communications graph $G(V, E)$, to model the network, where each node $v \in V$ corresponds to a mobile node in the network and E is the set of communications links each connecting a pair of nodes. There is a link $l = (u, v) \in E$ between nodes u and v, if two nodes are in the transmission range. A communication link $l = (u, v)$ denotes that u can transmit directly to v if there are no other interfering transmissions. Due to the broadcast nature of the wireless links, transmission along a link may interfere with other link transmissions when transmitted on the same channel.

An interference model defines which set of links can be active simultaneously without interfering. We model the impact of interference by using the well-known protocol model proposed in [22]. A transmission on channel c through link l is successful if all interferers in the neighborhood of both nodes u and v are silent on channel c for the duration of the transmission. Two wireless links (u, v) and (x, y) interfere with each other if they work on the same channel and any of the given expressions is true: $v = x$, $u = y$, $v \in Nb(x)$, or $u \in Nb(y)$, where $Nb(v)$ represents the set of neighbors of node v. If links (u, v) and (x, y) are conflicting, nodes u and y are within two-hops of each other [23].

4. Energy Efficient Multichannel MAC Protocol

Before starting the description of our proposed protocol, let us discuss the problem of popular multichannel MAC protocol, MMAC [12]. MMAC protocol uses only one ATIM window for multiple channels, so (C-1) ATIM windows are wasted. Furthermore, all nodes exchange ATIM/ATIM-ACK/ATIM-RES control packets to obtain the rights to access data channels on one channel, which leads to a high probability of control packet collisions. Consequently, neighboring nodes may fail to listen to a packet of a selected data channel. Thus, this will lead to data collision on the selected channel. The channel utilization of MMAC is shown in **Fig. 1**.

The structure of the proposed EM-MAC protocol is depicted in **Fig. 2**. We assume that system time is divided into fixed-length beacon intervals and each beacon interval consists of an ATIM window, and a communication widow. The ATIM window, which is divided into the beacon and the control window, is contention-based and uses the same mechanism as in the IEEE 802.11 DCF. A TDMA scheme is used in the communication window. Although the EM-MAC scheme has some similarities with both MMAC [12] and TMMAC [16] but our protocol is fundamentally different from them because the control information is not based on common control channel (CCC). Assume that default channel is channel 0. All nodes broadcast their beacons on channel 0, which is also used for global synchronization. In the beacon period, all nodes listen to channel 0 and wait for a backoff time to broadcast their beacon packets.

A channel-timeslot pair (c, t) is defined as the “communication segment”. In the control window, the pair source and destination compete for selection of communication segment to transmit data packets. After competing in the control window, the winning pair source and

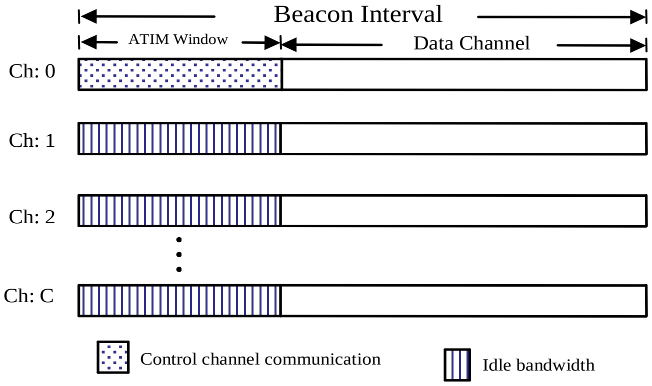


Fig. 1. Channel utilization of MMAC protocol.

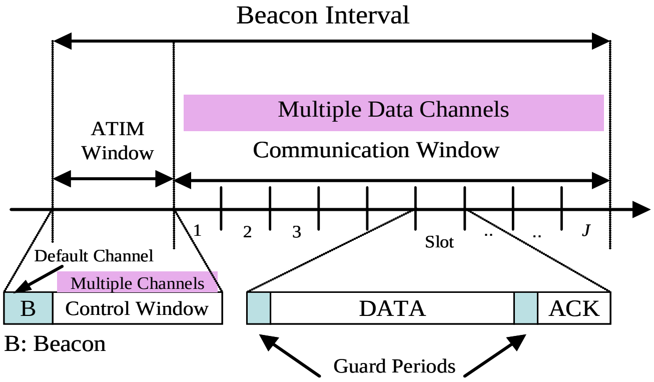


Fig. 2. Structure of the proposed EM-MAC protocol.

destination will be able to use the communication segment in the communication window. In MANETs, the number of nodes is usually greater than the number of channels. Therefore, there are many pairs of sources and destinations that compete for the communication segments in the control window. Thus, for increasing the channel utilization and to decrease the control packet collisions in the control window, instead of using only channel 0 all multiple channels are used in our EM-MAC protocol for selecting communication segments. From **Fig. 3**, it can be observed that the channel utilization of the EM-MAC protocol is higher than that of the MMAC protocol. Furthermore, the control packet collisions will decrease by distributing the source and destination pair in different channels to compete for the communication segments.

As mentioned earlier, the communication window is time-slotted and uses TDMA scheme. The duration of each timeslot is the time required to transmit or receive a single data packet and it depends on the data rate of PHY layer and the size of data unit. The duration of the timeslot is long enough to accommodate a data packet transmission, including the time needed to switch the channel, transmit the data packet and the acknowledgement (ACK). According to our MAC structure, the duration of each slot is given by

$$D_{slot} = D_{data} + D_{ACK} + 2 \times D_{guard} \tag{1}$$

The use of guard period is to accommodate the propagation delay and the transition time from transmitting (T_x) mode to receiving (R_x) mode. In the communication window, nodes can send or receive packets or go to sleep mode to save power. If a node has decided to send or receive a packet in the j^{th} timeslot of c^{th} channel, it first switches to that channel and transmits or waits for the data packet in that timeslot. If a receiver receives a unicast packet, the receiver sends

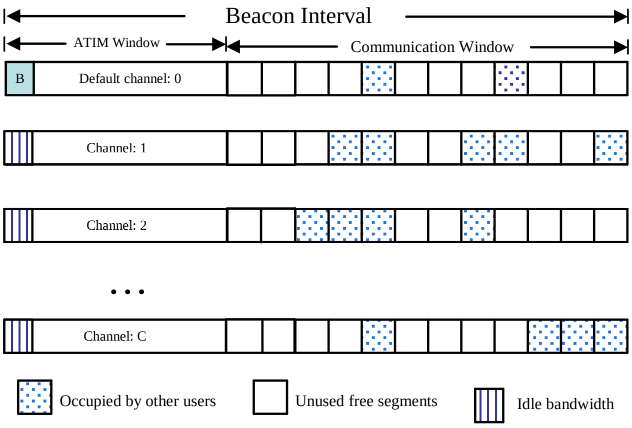


Fig. 3. Channel utilization of EM-MAC protocol.

back an ACK in the same timeslot. If a sender does not hear an ACK after it sends a unicast packet, may be because of the collision with other transmissions, the sender may perform random backoff before attempting its retransmission. If the number of retransmissions exceeds the retry limit, the packet is dropped. If a node has not decided to send or receive a data packet in the j^{th} timeslot, the node switches to sleep mode for power saving. To assure collision-free communications, all neighborhood nodes of the intended receiver except the intended transmitter should remain silent on the particular channel during a given timeslot.

With the help of periodic beaconing, each node is aware of (1) the identities and list of available communication segments within its two-hop neighbor, and (2) existing transmission schedule of communication segments of its one-hop neighbor. Based on the collected neighbor information and its own information each node updates the status of its communication segments as occupied or free. Free communication segment of node *v*, *free_segment(v)*, is defined as the communication segments for all channels, which are not used by node *v* to communicate with adjacent nodes, and are not interfered by other transmissions. Status of the communication segments on a link is determined by finding the intersection of the status of both end nodes of the link.

We define the set of common free communication segments between two nodes to be the link bandwidth. If we let *B(u, v)* be the available bandwidth of the link between nodes *u* and *v* then $B(u, v) = free\_segment(u) \cap free\_segment(v)$. For each link in the network, the communication segment assignment algorithm marks each communication segment as one of the following:

- Occupied: this segment is using by other transmissions and hence can not be used.
- Free: unassigned idle segment.
- Assigned: this segment might be used for newly scheduled transmission on a specific link.

4.1 Solution of Multichannel Hidden Terminal Problem

Suppose that in **Fig. 4** node *A* has packets for *B* and thus *A* sends an ATIM packet to *B* during the ATIM window, a list of free communication segments of *A* included in the packet. On receiving the ATIM request from *A*, *B* decides which segments to use during the beacon interval, based on its free communication segments and free communication segments of *A*. The communication segment selection procedure is discussed in the next sub section. After selecting the communication segments, *B* sends an ATIM-ACK packet to *A*, specifying the

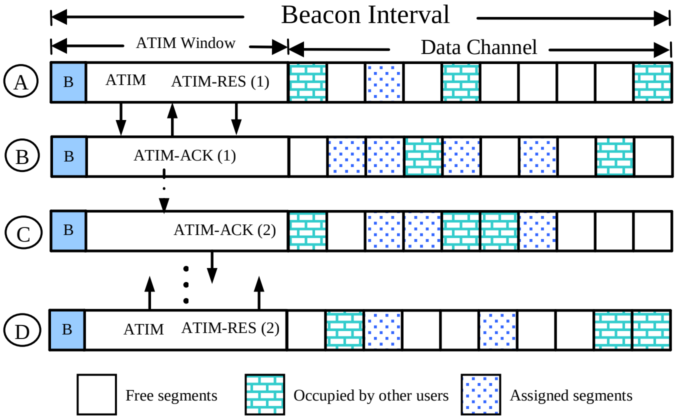


Fig. 4. Solution of multichannel hidden terminal problem using EM-MAC protocol.

channel and timeslots it has chosen. When *A* receives the ATIM-ACK packet, *A* will see if it can also select the same channel-timeslot specified in the ATIM-ACK packet. If it can, it will send an ATIM-RES packet to *B*, with selected channel-timeslots of *A* specified in the packet. If *A* cannot select the channel-timeslots which *B* has chosen, it does not send an ATIM-RES packet to *B*.

The process of communication segment assignment and data exchange in EM-MAC is illustrated in **Fig. 4** and shows how multichannel hidden terminal problem can be solved by using our EM-MAC protocol. During the ATIM window, *A* sends ATIM to *B* and *B* replies with ATIM-ACK indicating to use channel 1 and timeslots as per QoS requirement. This ATIM-ACK is overheard by *C*, so channel 1 will not be selected by *C*. When *D* sends ATIM to *C*, *C* selects channel 2 and required timeslots. So, after the ATIM window, the two communications (between *A* and *B* & between *C* and *D*) can take place simultaneously in the communication window.

4.2 Assignment of Communication Segments

In this subsection, we present a heuristic algorithm to assign communication segments for the link $l = (u, v)$. To ensure the collision-free transmissions, the following conditions must be satisfied in selecting the communication segments (c, t) to assign for the link $l = (u, v)$:

- Timeslot t is not assigned to any link incident (connected) on node u,
- Timeslot t is not assigned to any outgoing link from the node v,
- Timeslot t is not used on channel c by any link l', $T_x(l') \in Nb(v)$, and
- Timeslot t is not used on channel c by any link l', $R_x(l') \in Nb(u)$.

Here $T_x(\cdot)$ and $R_x(\cdot)$ represent the set of transmitters and receivers, respectively, of the given link. Note that one of the necessary constraints for collision-free communication is that no two links incident at a node can be assigned the same channel-timeslot [23]. If all of the above conditions are satisfied, the communication segment (c, t) is assigned to the link $l = (u, v)$. This procedure continues until the QoS (bandwidth) requirement is satisfied.

5. Analytical Model

To estimate the capacity of EM-MAC protocol, in this section, we present an analytical model to compute the saturated throughput and delay for both EM-MAC and single channel MAC in

IEEE 802.11 DCF in WLANs based on Markov chain model presented in [24] [25]. Although multi-hop networks are more complicated than WLANs, the analytical study based on WLANs offer better understanding of the performance of EM-MAC. **Table 1** shows the definitions of the system parameters used in this analysis.

Table 1. List of system parameters used in analysis

Symbols	**Definitions**
n	Number of nodes contending for contending for the channel
τ_i	A node transmits a packet in priority *i* during the timeslot
$P_{tr,i}$	Probability that at least one node try to transmit a packet
$P_{succ,i}$	Probability that a current packet transmission is successful
$T_{succ,i}$	Time spent in a successful transmission
$T_{coll,i}$	Time spent in a collision
L_R	Retry limit and maximum backoff stage
S	Saturated throughput
H	PHY and MAC layer headers
P	Packet payload size
R	Bit rate
C	Number of channels
δ	Propagation delay
SD	Saturation delay

We have developed the analytical model based on the Markov chain model for IEEE 802.11e enhanced distributed channel access (EDCA). In order to compute the saturated throughput and delay for multichannel networks, we adopt the analytical model developed in [24] [25] based on the IEEE DCF MAC mechanism. When we consider the relation between packet size and saturated throughput, we shall attempt to find the optimal trade-off between them.

We first assume that every node always has an available packet for transmission in which the probability τ_i of a packet being transmitted from a node in a slot can be represented as

$$\tau_i = \sum_{j=0}^{L_R} b_{i,j,0} = \sum_{j=0}^{L_R} p_i{}^j . b_{i,0,0} = \frac{1-p_i^{L_R+1}}{(1-p_i)} . b_{i,0,0} \tag{2}$$

where $b_{i,0,0}$, $b_{i,j,0}$ represent the initial and *j* stage, p_i stands for the probability that a transmitted packet encounters a collision when two or more nodes try to transmit their packets, $p_i{}^j$ is the collision probability in *j* stage, and $1-p_i^{L_R+1}$ is the probability that the packet is not dropped since the packet drop probability is $p_i^{L_R+1}$. p_i can be defined as

$$p_i = 1-(1-\tau_i)^{n_i-1} \prod_{h=1,h\neq i}^{N} (1-\tau_h)^{n_h} \tag{3}$$

where $p_i \in [0, 1]$ and $\tau_i \in [0, 1]$. We can easily calculate the two parameters τ_i and p_i from (2) and (3) based on [24] using numerical methods.

Let $p_{tr,i}$ denote the probability that there is at least one node within a timeslot, and $p_{succ,i}$ is the probability that a transmission is successful. They can be expressed as

$$p_{tr,i} = (1-(1-\tau_i)^{n_i}) \prod_{h=1,h\neq i}^{N} (1-\tau_h)^{n_h} \tag{4}$$

$$p_{succ,i} = \frac{\left(\begin{pmatrix} n_i \\ 1 \end{pmatrix} . \tau_i . (1-\tau_i)^{n_i - 1}\right)}{(p_{tr,i})} \tag{5}$$

For simplicity, we can present the saturated throughput $S_{i,j,k}$ based on the access mechanism of IEEE 802.11 DCF as the ratio

$$\begin{aligned} S_{i.j.k}^{\sin gle} &= \frac{E[\text{payloadinformation transmitted in a timeslot}]}{E[\text{lengthof a timeslot}]} \\ &= \frac{p_{tr,i} . p_{succ,i} . E[P]}{E[I] + p_{tr,i} . p_{succ,i} . T_{succ,i}^{\sin gle} + p_{tr,i} . (1 - p_{succ,i}) . T_{coll,i}^{\sin gle}} \end{aligned} \tag{6}$$

where $E[P]$ is the packet payload size, $p_{tr,i} . p_{succ,i} . E[P]$ is the average amount of successfully transmitted payload information. The average length of time period consists of $E[I]$, the expected value of an empty timeslot, and $p_{tr,i} . p_{succ,i} . T_{succ,i}$ is the time that a successful transmission without collision, and $p_{tr,i} . (1 - p_{succ,i}) . T_{coll,i}$ is the time that a successfully transmission with collision. Suppose that R_{EM} represents bit rate, in which C is the number of channels.

$$R_{EM} = \frac{bit}{\frac{Time}{C}} = \frac{C.bit}{Time} \text{ bits/sec} \tag{7}$$

For simplicity, we assume that maximum R_{EM} equals to the average maximum saturated throughput, which can be represented as

$$S_{i,j,k}^{EM} = \frac{C . p_{tr,i} . p_{succ,i} . E[P]}{E[I] . p_{tr,i} . p_{succ,i} . T_{succ,i}^{EM} + p_{tr,i} . (1 - p_{succ,i}) . T_{coll,i}^{EM}} \tag{8}$$

To determine saturated throughput, we also need the corresponding values of $T_{succ,i}$ and $T_{coll,i}$ in terms of single channel and multichannel, respectively. These parameters can be defined as

$$\begin{aligned} T_{s,i}^{\sin gle} &= RTS + SIFS + CTS + SIFS + H + P \\ &\quad + SIFS + ACK + DIFS \\ T_{c,i}^{\sin gle} &= RTS + SIFS + CTS\_Timeout + DIFS \end{aligned} \tag{9}$$

$$\begin{aligned} T_{s,i}^{EM} &= ATIM + SIFS + \delta + ATIMACK + SIFS + \delta \\ &\quad + H + P + ATIMRES + DIFS + \delta \\ T_{c,i}^{EM} &= ATIM + SIFS + CTS\_Timeout + DIFS \end{aligned} \tag{10}$$

where δ is the propagation delay, H is the PHY and MAC layer headers, and P is the packet payload size.

In addition, we also carryout the packet delay analysis of multichannel EM-MAC protocol in comparison with that of single channel MAC. The saturation delay $SD_{i,j,k}$ is defined as the average time interval until it is successfully transmitted. When the packet transmission has reached the preset retry limit, it will be dropped. The average saturation delay of single channel is defined as

$$E[SD_{i,j,k}] = E[X_i]\ .\ [\text{length of a timeslot}] \tag{11}$$

where $E[X_i]$ is the average time interval required for effectively transmitting a packet. We can finally derive

$$E\left[X_i\right] = \sum_{j=0}^{L_R} \left[\frac{\left(p_i^j - p_i^{L_R+1}\right) . \dfrac{W_{i,j}+1}{2}}{1 - p_i^{L_R+1}} \right] \tag{12}$$

when transmission of data packet reaches the preset retry limit, it is noticeably dropped. $\left(p_i^j - p_i^{L_R+1}\right) / \left(1 - p_i^{L_R+1}\right)$ is the probability that a packet that is not discarded and reaches the j stage. To estimate saturation delay for multichannel EM-MAC, we can adopt the fundamental principle of TDMA scheme.

$$D_{EM} = w\ (latency\ time) + \tau\ (transmission\ time) \tag{13}$$

$$w = \frac{1}{C} \sum_{m=1}^{M} (m-1) \frac{T}{C} = \frac{T}{C^2} \sum_{n=1}^{M-1} n$$

$$= \frac{T}{C^2} \frac{(C-1)C}{2}$$

$$w = \frac{T}{2}\left(1 - \frac{1}{C}\right) \tag{14}$$

$$\tau = \frac{T}{C} = \frac{bit}{L_{R,EM}} \tag{15}$$

$$D_{EM} = \frac{T}{2}\left(1 - \frac{1}{C}\right) + \frac{T}{C} \tag{16}$$

We assume that the average saturation delay $E[SD_{i,j,k}]$ equals to total time T according to D_{EM} as defined above. As a result, we can derive the average saturation delay of multichannel EM-MAC as the parameters for the multichannel as follows

$$E\left[SD_{EM}\right] = \frac{E\left[SD_{i,j,k}\right]}{2}\left(1 - \frac{1}{C}\right) + \frac{E\left[SD_{i,j,k}\right]}{C} \tag{17}$$

6. Performance Evaluation

The effectiveness of the proposed EM-MAC protocol is validated through computer simulation. This section describes the simulation environment and the experimental results. To evaluate EM-MAC protocol, we have developed a packet-level discrete-event simulator written in C++ programming language, which implements the features of the protocol stack described in this paper. The result of our approach is compared with IEEE 802.11 DCF [10], MMAC [12], TMMAC [16], and CD-MAC [17].

The simulated network is composed of 100 nodes deployed randomly within a 500 m × 500 m square region. The transmission and interference range of each node is approximately 150 m and 300 m respectively. The two-ray-ground reflection model is used as propagation model. We set an initial energy of 100 Joules per node and the transmitting energy of each node: *ETx* = (1.65 × packet size in bits)/2 × 10^6 Jules, and the receiving energy: *ERx* = (1.15 × packet size in bits)/2 $\times 10^6$ Jules [26]. Nodes move randomly according to the random waypoint mobility model. In all simulations, nodes choose a speed uniformly distributed between 0.5 and 3 m/s, which regard as the range of human walking speeds in an indoor environment. To provide a highly dynamic scenario, we set the pause time to zero seconds on all simulations. The simulation parameters are summarized in **Table 2**.

Table 2. Simulation parameters

Parameters	Value
Terrain size	500 m × 500 m
Number of nodes	100
Node placement	Random
Number of channels	4-12 (1 for CCC and others for data)
Data rate	2 Mbps (both data and control channel)
Data packet size	1000 bytes
Channel switching delay	80 µs
Transmission range	150 m
Interference range	300 m
Beacon interval	42 ms
Length of the communication window	34 ms
Timeslots in communication window	8 (4.5 ms each)
Length of the ATIM window	8 ms (control: 5.5 ms, beacon: 2.5 ms)
Propagation model	Two-ray-ground reflection model
Mobility model	random waypoint mobility model
Node moving speed	uniformly distributed between 0.5 and 3 m/s
Pause time	0 s (a highly dynamic scenario)
Node initial energy	100 Joules
Transmitting energy	$ETx = (1.65 \times \text{packet size in bits})/2 \times 10^6$ Jules
Receiving energy	$ERx = (1.15 \times \text{packet size in bits})/2 \times 10^6$ Jules
Bandwidth (QoS) requirement	1-4 timeslots
Simulation time	600 s

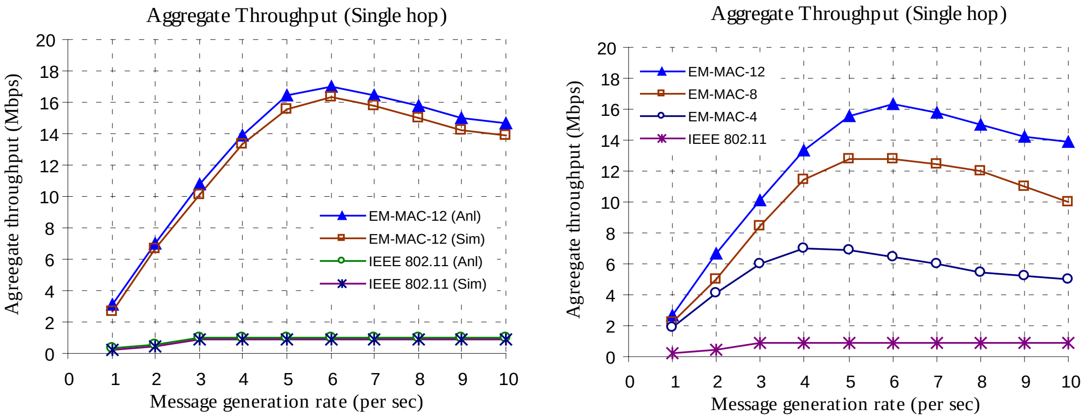
Assume that beacon interval for the MAC scheme is set to 42 ms where the communication window is 34 ms. The number of timeslots in the communication window is set to 8 and each slot duration is 4.25 ms, which is calculated for a 1000 bytes packet to be sent through the channel of data rate 2 Mbps. The length of the ATIM window is 8 ms where 2.5 ms is assigned for beacon period. Channel switching delay is set to 80 µs. We vary the number of channels from 4 to 12, each of which has a data rate of 2 Mbps. Among them, one channel is CCC and the others are data channels. Statically chosen shortest path routing is used to show the performance in multi-hop scenario. We initiate route request (RREQ) between randomly selected but disjoint source-destination pairs. The bandwidth (i.e. number of timeslots) requirement in a RREQ is sets to a random integer from the range [1, 4].

We impose the best effort traffic with message generation time exponentially distributed with mean value 1/{(message generation rate)/(number of nodes)} s. Average message length is geometrically distributed with mean value 4000 packets. We vary the message generation rate to vary the offered load to the network. Each data point in the plots is an average of 10 runs where each run uses a different random network topology. The simulation time of each run is set to 600 seconds.

The following performance metrics are used to evaluate the proposed EM-MAC protocol:

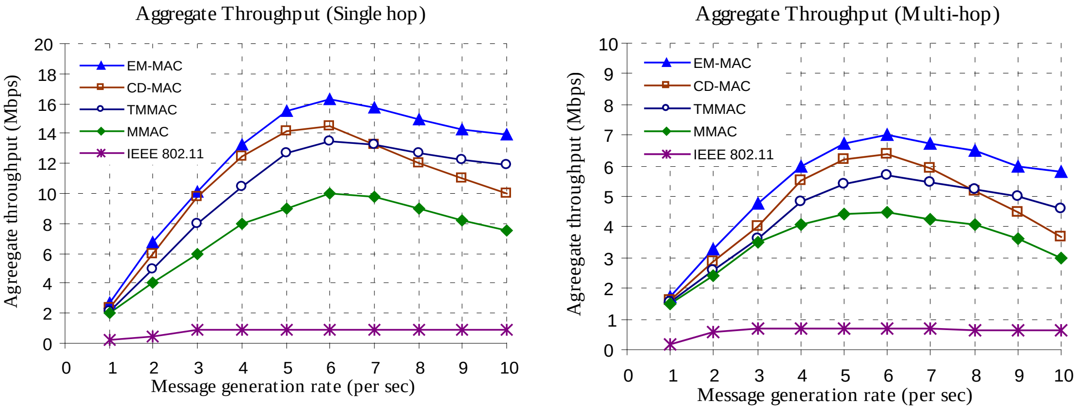
- *Aggregate Throughput*: Total bits received per second by the destinations.

- *Average End-to-End Delay*: Average latency incurred by the data packets between their generation time and their arrival time at the destinations.
- *Energy Efficiency*: The energy efficiency that is measured in data packets delivered to the destinations per Joule.
- *Network Lifetime*: The duration from the beginning of the simulation to the first time node runs out of energy.



(a) Aggregate throughput of EM-MAC and IEEE 802.11 in single hop scenario.

(b) Aggregate throughput of EM-MAC with different number of channels compared with IEEE 802.11 in single hop scenario.



(c) Comparison of aggregate throughput of EM-MAC with other protocols in single hop scenario.

(d) Comparison of aggregate throughput of EM-MAC with other protocols in multi-hop scenario.

Fig. 5. Aggregate throughput of EM-MAC protocol in single hop and multi-hop scenario by varying offered load.

In **Fig. 5**, we measured the aggregate throughput by varying the offered load. **Fig. 5-(a)** shows the aggregate throughput of the numerical and simulation results of our proposed EM-MAC protocol with 12 channels and IEEE 802.11 with single channel, where “Anl” and “Sim” represents the numerical (analytical) results and the simulation results, respectively. Our simulation results are very close to the analytical results. The effects of aggregate throughput on the number of channels are shown in **Fig. 5-(b)** in single hop scenario. In the graphs "EM-MAC-12" indicates EM-MAC protocol with 12 channels, and "IEEE 802.11" indicates IEEE 802.11 DCF with single channel. We can see from the **Fig. 5-(b)**, when the offered load (message generation rate) increases, aggregate throughput increases up to message generation rate 6 and then slightly decreases till the end of the simulation. EM-MAC with 12 channels outperforms in all level of offered load compare to the other cases. Throughput of EM-MAC with 12 channels achieves 18 times of IEEE 802.11, 2.32 times of EM-MAC with 4 channels, and 1.27 times of EM-MAC with 8 channels.

Fig. 5-(c) compares the aggregate throughput of EM-MAC with other protocols in single hop scenario having 12 channels. As we can see from the **Fig. 5-(c)**, when the offered load increases, EM-MAC offers significantly better performance than all other protocols especially compared with IEEE 802.11. When the network is saturated, EM-MAC achieves 12.27 % more throughput than CD-MAC, 20.59 % more than TMMAC, and 62.8 % more than MMAC protocol. After reaching the saturation points, the throughput of CD-MAC and MMAC decrease quickly due to the high offered load, which creates more contentions in data communications as both protocols are contention-based. Our protocol outperforms all other protocols because we exploit contention-free communications and instead of using only CCC, multiple channels are used in ATIM window for channel-timeslots selection.

Fig. 5-(d) shows the performance of EM-MAC on multi-hop cases. When the network is saturated, EM-MAC achieves 9.38 % more throughput than CD-MAC, 22.8 % more than TMMAC, and 55.55 % more than MMAC and 10 times of IEEE 802.11. The main reason of higher aggregate throughput in EM-MAC is when the message generation rate is high; the available channel diversity can be better exploited by our EM-MAC protocol. That's because the channel assignment algorithm can balance the channel load, so the traffic is allocated on different channels in an approximately average manner. Finally, EMQ-MAC achieves higher performance because EM-MAC eliminates inter-flow and intra-flow interference using a non-conflicting channel-timeslots assignment scheme.

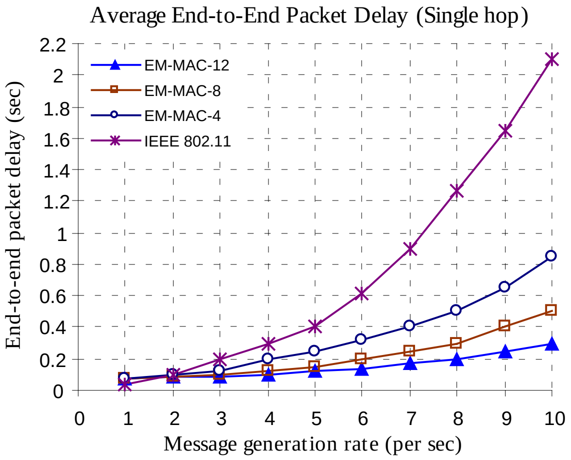


Fig. 6. Average end-to-end packet delay of EM-MAC protocol with different number of channels in single hop scenario by varying offered load.

Fig. 6 and **7** present the average end-to-end packet delay by varying the message generation rate for single hop and multi-hop scenarios. The effects of the number of channels on the average end-to-end packet delay are shown in **Fig. 6**. EM-MAC with 12 channels shows lower delay in all level of the offered load. **Fig. 7** shows the comparison of average end-to-end

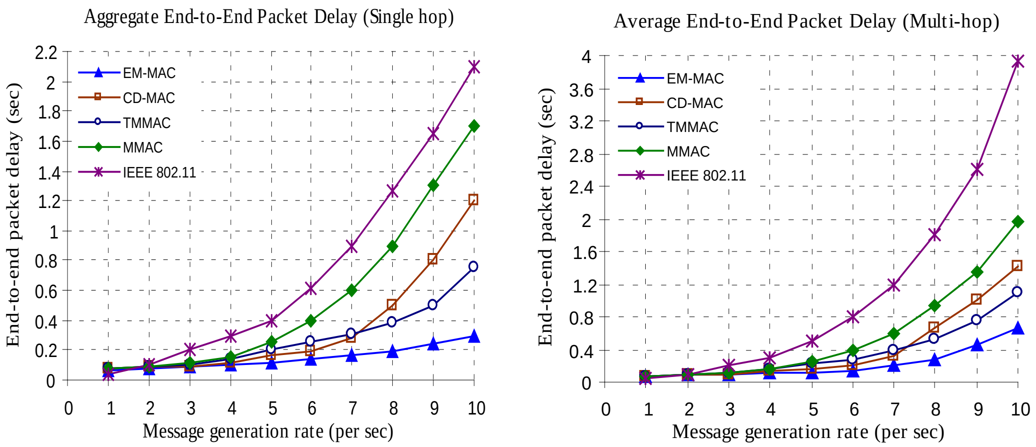


Fig. 7. Comparison of average end-to-end packet delay of EM-MAC protocol with other protocols in single hop and multi-hop scenario by varying offered load.

packet delay of the protocols as the network load increases. The difference between IEEE 802.11 DCF and other protocols in delay is due to the fact that with only one channel, a packet has to wait longer to use the channel when the network load is high. When comparing with other protocols EM-MAC shows lower delay in all network scenarios. IEEE 802.11 DCF achieves better performance than other schemes when the message generation rate is low. However, when load increases, queuing delay is raised. The queuing delay makes the performance of each protocol worse. Specially, the end-to-end packet transmission delay of IEEE 802.11DCF is increased dramatically because IEEE 802.11 DCF uses only a single channel for data transmission. On the other hand, the data traffic is split into multiple channels in the case of EM-MAC. Therefore the end-to-end packet transmission delay of EM-MAC is increased slowly according to increase of offered load.

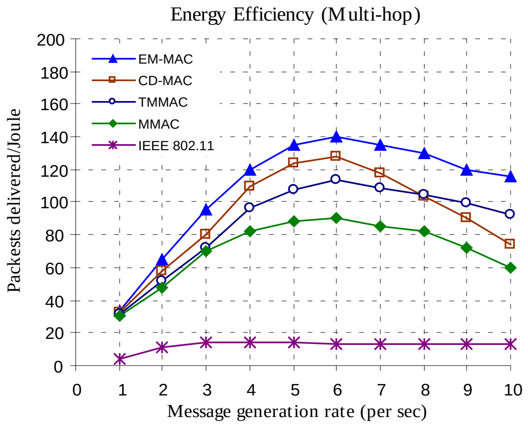


Fig. 8. Comparison of energy efficiency of EM-MAC with other protocols.

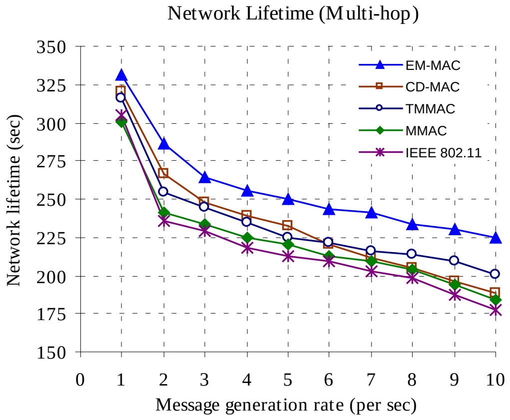


Fig. 9. Comparison of network lifetime of EM-MAC with other protocols.

The comparisons of the energy efficiency of the protocols are shown in **Fig. 8**. The graph shape is identical with aggregate throughput. It is shown in the figure that received packets at the destinations per Joule increase up to the saturation level of the offered load and then slightly decrease till the end of simulation. Our proposed EM-MAC protocol shown more energy efficient compared to other protocols. The network lifetime is shown in **Fig. 9**. Our proposed EM-MAC protocol handles battery energy in an efficient way thus prolonging the lifetime of individual nodes and overall network as well. When the offered load increases the network lifetime decreases because of the increasing of the number of routes.

7. Conclusions

In this paper, we present the EM-MAC protocol, which is a multichannel MAC protocol using a single half-duplex transceiver for QoS provisioning in MANETs. Nodes that have packets to transmit, negotiate which channels and timeslots to use for data communications with their destinations during the ATIM window. This two-dimensional negotiation enables EM-MAC protocol to exploit the advantage of both multiple channels and TDMA in an energy efficient manner. Further, EM-MAC is able to support broadcast in an effective way. Since EM-MAC only requires one transceiver per node, it can be implemented with hardware complexity comparable to IEEE 802.11. Also, power saving mechanism used in IEEE 802.11 can easily be integrated with EM-MAC for energy efficiency without further overhead. Simulation results show that EM-MAC successfully exploits multiple channels to improve aggregate network throughput and the average end-to-end packet delay. Extensive simulations confirm the efficiency of EM-MAC and demonstrate its capability to provide high throughput for robust single hop and multi-hop communications. EM-MAC can also be used for communications under unknown and dynamic traffic conditions, i.e. disaster recovery or military operations.

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