DH-MAC : A Dynamic Hybrid MAC Protocol with the mechanisms of TDMA and CSMA/CA

Xiaoyi Ge, Songjun Ma, Xiaohua Tian, Xinbing Wang
Department of Electronic Engineering Shanghai Jiao Tong University, Shanghai, China

ABSTRACT - **With the explosive increase in the number of mobile devices and applications, it is anticipated that wireless traffic will increase exponentially in the coming years. The existing MAC protocols have not satisfied the increasing demands of wireless traffic. This paper presents the design, mathematic analysis, and performance evaluation of a dynamic hybrid MAC protocol, DH-MAC, with the mechanisms of TDMA and CSMA/CA. But DH-MAC is unlike some other hybrid models which directly divides time slots into TDMA mode and CSMA/CA mode. It maximizes, on the one hand, the advantages and, on the other hand, also minimizes the disadvantages of both models. In the further step, this paper analyzes the mathematic performance of DH-MAC, especially including the analysis of scheduling policies of the transmission queue. Finally, it present the results of simulation with Matlab and GCC compiler, which shows that the hybrid model has a relatively constant efficiency regardless of the number of transmitting nodes.**

KEYWORDS - **MAC, TDMA, CSMA/CA, hybrid model, dynamic time slot**

I. Introduction

A. Background

With the advent of broadband wireless transmission, the increasing popularity of mobile devices, and the deployment of wireless sensor networks, wireless networks are increasingly used to serve real-time flows that require strict per-packet delay bounds. Such applications include VoIP, video streaming, real-time surveillance, and networked control. For example, a study [1] has predicted that wireless traffic will grow exponentially, and that mobile video will dominate wireless traffic in the near future, accounting for 62% of wireless traffic by the year 2015. So in this rapid trend of development, there is a strong need for a reliable and well-performed MAC protocol to support the daily communication for all the applications.

But what kind of work MAC layer do to make the system work well? It's indeed a good question, actually. In one word, scheduling, as shown in the Fig. 1. The MAC layer just schedule all the APs (Access Point) and all the users, both primary users and secondary users, in the system and let them to work jointly to make the whole system have the as good performance as possible. And as with scheduling methods, a MAC protocol must make the different links,

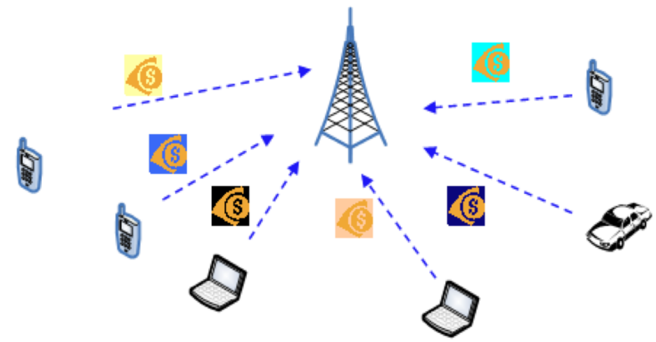

Fig. 1. Scheduling work in a centralized network.

including uplinks and downlinks, have the static transmission, avoiding collisions with each other. In the wireless network, there are two different approaches to avoid collisions. One is a centralized approach where a scheduler (AP) chooses a set of non-interfering links to transmit at each time slot. Most cellular network protocols, such as WiMax and LTE, use this approach. Another is a distributed approach where each wireless node chooses whether to transmit or not based on its observation of system history. And in this paper, we only focus on the first link model and set an AP in the system, which has all the information of all the user nodes around it. And thus the AP can schedule all the transmission orders of user nodes.

B. Basic knowledge for CSMA/CA and TDMA

In the recent years, IEEE has standardized the 802.11 protocol for WLAN (Wireless Local Area Networks) [2]. Then the final version of the IEEE standard has recently appeared, and provides detailed Medium Access Control (MAC) and Physical layer (PHY) specification for WLANs. In the 802.11 protocol, the fundamental mechanism to access the medium is called Distributed Coordination Function (DCF). This is a random access scheme, based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. Retransmission of collided packets is managed according to binary exponential back-off rules. The standard also defines an optional Point Coordination Function (PCF), which is a centralized MAC protocol able to support collision free and time bounded services. The default scheme is a two-way hand-shaking technique called Basic Access mechanism. This mechanism is characterized by the immediate transmission of a positive acknowledgement (ACK). In addition to the Basic Access, an optional four way hand-shaking technique, known as Request-To-Send/Clear-To-Send (RTS/CTS) mechanism has been standardized. Before transmitting a packet, a station operating in RTS/CTS mode "reserves" the channel by sending a special Request-To-Send short frame. The destination station acknowledges the receipt of an RTS frame by sending back a Clear-To-Send frame, after which normal packet transmission and ACK response occurs. The whole mechanism is shown in the Fig. 2.

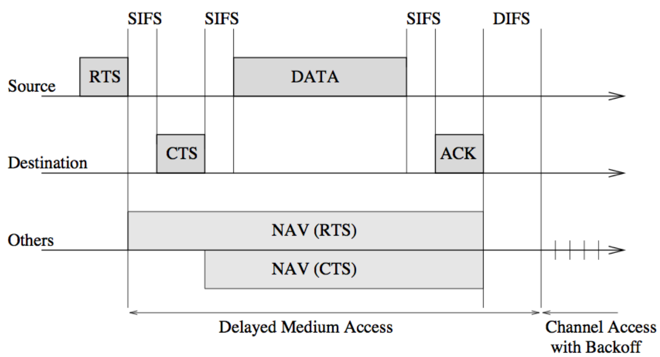

Fig. 2. A hand-shaking four-way RTC/CTS access mechanism of the CSMA/CA model.

But one major disadvantage of CSMA/CA is that with too many users existing in the system, it will have a very long time period used for backing-off to avoid the collision. And another disadvantage of CSMA/CA is that it uses a large amount of energy to listen to the channel to get prepared for coming packets and signals. And in order to improve the both weaknesses of the CSMA/CA model, then the TDMA model appears. In the TDMA model [4], the AP has the information of all transmitting nodes before the transmission of user nodes in each time period and then schedule them to transmit their data one by one in the different time slots. So in this way, there are two major advantages. One is that each user node has the knowledge of when to transmit and cause no collision at all. The other is that user nodes will wake up at the certain time points in every time period, reducing the energy consumed for listening to the channel, waiting for the signals to transmit. The mechanism of the TDMA model is shown in the Fig. 3.

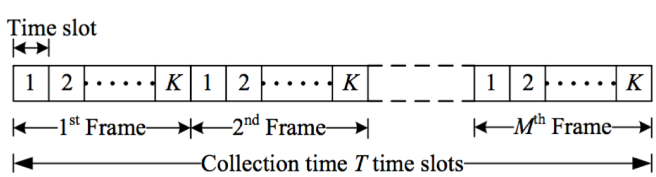

Fig. 3. The mechanism of the TDMA model.

C. Motivation

Considering the knowledge mentioned above, we can see it that under low channel contention, the CSMA/CA model has a better channel utilization; and also similarly under high channel contention, the TDMA model then achieves better performance. So why don't we design a hybrid dynamic MAC model, DH-MAC? Like CSMA/CA, this DH-MAC model achieves high channel utilization and low latency under low contention and like TDMA, it also achieves high channel utilization under high contention and reduces collision among two-hop neighbors at a low cost [5]. But DH-MAC is unlike some other hybrid models [6] which directly divides time slots into TDMA mode and CSMA/CA mode. This hybrid model has the advantages of both models and minimize their disadvantages as well as possible. In this way, we can get a hybrid model that has a relatively constant and high performance compared with other two basic models. Although perhaps the CSMA/CA model may have a little higher performance under low contention or the TDMA model may have under high contention, the hybrid model must have the overwhelming highest average performance in the long run.

II. Related Work

Both S-MAC [7] and T-MAC [8] are a hybrid of CSMA and TDMA in that they also maintain the synchronized time slots, but, unlike TDMA, their slots can be much bigger than normal TDMA slots and synchronization failures do not necessarily lead into communication failure because they employ RTS/CTS. As these protocols use RTS/CTS mechanism, the overhead of the protocols is quite high because most data packets in sensor networks are small. T-MAC [8] improves the energy efficiency, based on S-MAC, by forcing all of the transmitting nodes to start their transmission at the beginning of each active period.

Also, B-MAC [9] is the default MAC for Mica2. B-MAC allows an application to implement its own MAC through a well-defined interface. They also adopt LPL (low power listening) [10] and engineer the clear channel sensing (CCA) technique to improve channel utilization. $CSMA/p^*$ [11] uses the optimal probability distribution in determining the channel access probability for CSMA when the number of transmitting nodes is known. When is unknown, it provides suboptimal performance. Sift adapts $CSMA/p^*$ [11] for a network where is unknown. The result has high success probability for channel access and reduced collision probability, thus achieving good throughput under both low and high contention. However, the optimal probability distribution works only when senders always have data to transmit and they are synchronized for the channel access, and, thus, when data arrivals to a node are highly random and senders cannot sense each other for data transmission (as in two-hops), its performance degenerates to the case of CSMA with the uniform access probability distribution. Sift relies on RTS/CTS to handle hidden terminals.

III. System Model

In our dynamic hybrid model, DH-MAC, the system model mainly consists of three parts. The first part is called as *information collection*. In this part, we will introduce the process of information collection. The information ensures the communication between the AP, the only center node, and the surrounding user nodes. The second part is called as *scheduling*. In the scheduling part, the AP will make the use of the information collected from all the near-by user nodes and thusly schedule all the user nodes to let them finish their transmission in a relatively high efficiency. And the third part is called as *transmission*. During the process of transmission, the user nodes may either normally finish their transmission in a certain time slot or finish their transmission ahead of time. Both situations will be well considered with the scheduling of AP.

A. Information Collection

Let us first consider a simple direct collection of information, as shown in the Fig. 4. Taking the hidden terminals into consideration, the collection of information may get trapped in a collision. Like the illustration of Fig. 4, if the two user nodes near the center node AP are sending their transmission request, or other information like that, to the center node at the same time, the collision will happen. And trapped in a collision, the center node will miss a transmission request and consequently the user node will not start its transmission in a long run. Even a collision may cause the system into chaos and break down eventually.

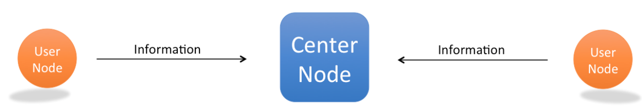

Fig. 4. A system with direct information exchange.

However, if we want to avoid the collision from happening, we can use the hand-shaking four-way mechanism like CSMA/CA. In the CSMA/CA model, we can conclude that if the multiple user nodes come into a collision, they will have a much longer back-off time to avoid collision. But in our DH-MAC model, the back-off time only exists in the process of information collection. So in this way, it can be a much shorter period of time.

To be specific, like the Fig. 5 shows, in the beginning of a time period, the AP will first send a *permission* signal to the surrounding user nodes. And if a user node wants to transmit their data, it first need to put itself into the transmission queue, which is recorded by the AP. Therefore, the user node who has the intention of transmitting data will send a *ready-to-send (RTS)* signal to the AP. When the AP receives the RTS signal successfully, it will send back a *acknowledgement (ACK)* signal to the user node to tell them message received successfully and then stop them sending RTS signal. Otherwise, the user node will keep sending RTS signals until the AP sends back the ACK signal. Thus, if two user nodes are sending the RTS signal at the same time, which is also called the collision in some way though, one of the user nodes just has to back off for a short time called back-off time. So in this way, collisions are avoided. The system is collision-free in the process of information collection.

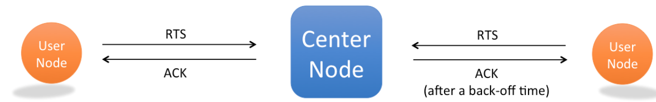

Fig. 5. A system with hand-shaking mechanism.

B. Scheduling

In the scheduling part, the AP will use a very short length of time period to schedule user nodes and make all the *transmission rules* in the time period. And these transmission rules consist of two jobs, transmission order and time period. The first job, transmission order, is to determine in what order all the users node transmit their data obey in order to make the system perform well. The second job, time period, is to determine what length the current time period will be, because with different numbers of transmitting nodes, the length of time period should also vary with that.

1) Transmission Order: In the above parts, after a short period of time in the very beginning of each time period, the AP will have the knowledge of the number of transmitting nodes as well as their serial number. And all the information is stored in the transmission queue in the AP. Actually, the AP still holds the information of last time period. Thus in this way the AP will just change the information of nodes who have finished their transmission or who will start their transmission in the next time period. And if the AP just keeps the record of the change of the transmitting nodes, it will save a big amount of energy and also simplify the process of scheduling. Then we consider a specific example, as shown in the Fig. 6. A system has a hundred user nodes and only one AP. The AP has to schedule all the 100 user nodes to let them have a good way to improve the system. For instance, during the last time period, the serial number of transmission queue is respectively 11, 72, 3, 24, 91, 54. And the number of transmitting nodes, CurNodeNum, is 6. And after last time period, the node 72 has finished its transmission and the node 29, 76, 18 have the intention of adding themselves into the transmission queue. So in the scheduling part of current time period, the AP only needs to delete the node 72 and add the node 29, 76, 18. And the current transmission queue is 11, 3, 24, 91, 54, 29, 76, 18. Also, the number of transmitting nodes is 6-1+2=8. That's the first part of scheduling the transmission order.

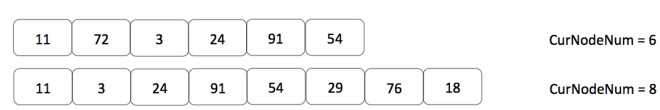

Fig. 6. An example of transmission queue.

Besides, it's also important to decide in what order all the transmitting nodes will start and finish their transmission. In general, the policy is called *largest debt first scheduling policies*. And the debt can have two different kinds. The first kind of debt is the time-based debt. And the second kind of debt is the weighted-delivery debt. Both debt first scheduling policies will be further discussed in the next section IV.

2) Time Period: In any real-time systems, the length of time period is supposed to have a close linear relationship with the number of transmitting node. That's because if there are too few nodes for a relatively long time period, then the new nodes will take a long time to connect themselves into the transmission queue. And on the contrary, if too many nodes for a short time period, the system will be busy dealing with signals like RTS, CTS or ACK, instead of transmitting data. That will cause the *thrashing*, which will low down the efficiency of the system in a great degree. So in order to avoid above two situations occurring, the AP needs to set an upper bound and a lower bound of the system. And these boundaries of the system will dynamically change according to the number of transmitting nodes. In general, the length of time period will double until it is larger than the lower bound; similarly, the length of time period will also halve until it is smaller than the upper bound. To be specific, this scheduling algorithm is shown in the Algorithm 1.

Algorithm 1 Dynamically determine the length of time period

Set the initial value of $time\_period = 2^n$
Set the upper bound for the system, N_1
Set the lower bound for the system, N_2
while $CurNodeNum < time\_period/N_1$ **do**
    time_period *= 2
end while
while $CurNodeNum > time\_period/N_2$ **do**
    time_period /= 2
end while
Get the final value of time_period

C. Transmission

In the above two subsections, we can get one way of uplink, information collection, and one way of downlink, scheduling. In the most parts of a time period, however, the AP is receiving data from the user nodes around itself. And this process of receiving data is called as *Transmission*, including both uplink and downlink. In this part of transmission, we can approximately divide the whole process into the four steps. The first part is determining maximum value of each time slot. The second part is giving the transmitting a clear-to-send (CTS) signal to let it to start transmission. The third part is waking up the next transmitting node to get it prepared for the CTS signal. The four part is dealing with those nodes who have finished transmission ahead of time.

In the first part of transmission, it aims at determining the maximum value of each time slot. If the AP is about to determine that, it must be aware of two relative values. One is the length of time period, which is only the length of transmission part. The other is the number of transmitting nodes. The length of time period has been dynamically decided in the scheduling part. And the number of transmitting nodes has also been decided in the information collection part. So the value of maximum value of each time slot can be calculated as following:

$$slot\_max = \frac{the\ length\ of\ time\ period}{the\ number\ of\ transmitting\ nodes}$$

So each transmitting node has to transmit their data in its own time slot. Normally like the traditional TDMA model, the transmitting nodes will continue to transmit their data in the next time period if they has not yet finished their transmission. But only if a transmitting node has finished their transmission ahead of time in this time period, this DH-MAC model will deal with those nodes. Thus we can say that the actual length of time slot is equal to or smaller than the max value of time slot. An example is shown as Fig. 7. In this example, there are 10 transmitting nodes intending to transmit their data. So the whole time period is divided into 10 slots. And each slot is smaller than or equal to a tenth of the time period. However, the slot 1 and slot 6 has finished their transmission ahead of time instead of till the end of the time slot. So these two slots are shorter than the other eight slots.

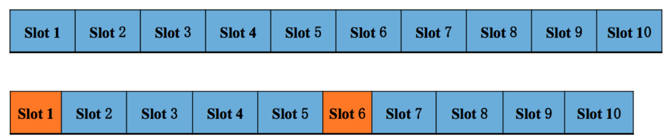

Fig. 7. A time period with 10 transmitting nodes.

In the second part of transmission, the AP will send one transmitting node a clear-to-send (CTS) signal to demand the transmitting node to start their transmission. Because this node has been in the mode of *wake_up*, it can start their transmission once they receive the CTS signal. And during the process of transmission, the user node keeps transmitting data to the AP until all the data is about to finish transmission.

In the third part of transmission, the AP will send the *WakeUp* signal to the next transmitting node. Because in the CSMA/CA model, it takes a large amount of energy to listening to the channel, waiting for the signal to start their transmission. But this part of energy consumption can be saved if the system is efficient enough. As our DH-MAC model shows, only when this transmit node start its transmission, then the next transmitting node is waked up. So in this way at most a time slot is used to listen to the channel, saving a great amount of energy for the user node. The Fig. 8 illustrates the second part and the third part of transmission process.

In the fourth part of transmission, the system is about to cope with the ending of each transmission time slot. As mentioned above, there are totally two states for user nodes to transmit their data. One state is that the user node has not yet finished their transmission in this time period. So this user node has to continue its transmission in a time slot of the next time period. We call this state as *normal state*. The other state is that the user node just finished their transmission in this time period. And it must be deleted from the transmission queue immediately. We call this state as *abnormal state*. The normal

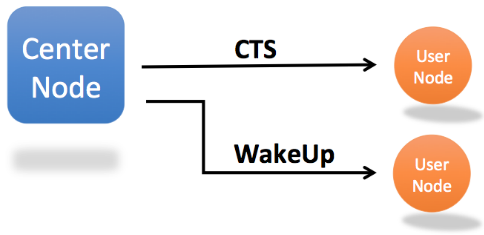

Fig. 8. AP sends CTS and WakeUp signal to user nodes.

state can be finished normally and the next transmitting node is ready for the transmission. This part mainly deal with the abnormal state. In that the transmitting nodes in the abnormal state is about to finish their transmission ahead of time, it must be dealt with in special ways. In our DH-MAC model, if one transmitting node is about to finish its transmission before the end of time slot, it will send back to the AP a signal called *Finish*. And if the AP receives this Finish signal, it will be aware of the fact this transmitting node has finished its transmission. Then the AP will send to the next transmitting node a signal called *Next*, in order to let the transmitting node start their transmission immediately. The transmitting node wakes up in the last time slot before their transmission, mainly waiting for the Next signal.

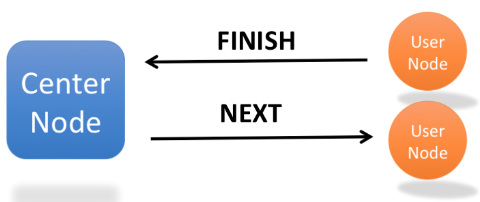

Fig. 9. The system deals with the end of transmitting nodes.

As mentioned in this section, the whole process of the system is completed. One major advantage of the DH-MAC is that the AP will always be busy dealing with any kinds of signals or receiving data from user nodes. And unlike traditional TDMA and CSMA/CA models, DH-MAC can have a relatively constant efficiency performance with the varying number of transmitting nodes.

IV. Mathematic Analysis

This section consists of three major parts of mathematic analysis. The first part is about the order of transmission queue. With different transmitting nodes in the transmission queue, there are supposed to be different transmission orders. That's because of different transmission demands. The second part is concerned with the system efficiency. Due to different transmission states, we can get different efficiencies. We are expecting the efficiency as high as possible. The third part works on the energy consumption, compared with the TDMA model and CSMA/CA model. It turns out that the DH-MAC model can have a relatively low energy consumption ratio, close to the TDMA model.

A. Transmission Queue

If we take the *largest debt first scheduling policies* as our scheduling policies, first we need to have several definitions and lemmas as following:

Definition 1 *A system is said to be* ***fulfilled*** *by some scheduling policy η, if, under η, the timely-throughput provided to each client η is at least q_n.*

Definition 2 *A system is* ***feasible*** *if there exists some scheduling policy that fulfills it.*

Definition 3 *A scheduling policy is* ***feasibility optimal*** *if it fulfills every feasible system.*

Lemma 1 *With the possibility of successful transmission p_n, the long-term average timely-throughput of a client n is at least q_n packets per interval if and only if the AP, on average, schedules that client $w_n := w_n(q_n) = \frac{q_n}{p_n}$ times per interval.*

Lemma 2 *A set of N clients is feasible only if $\sum_{n=1}^{N} w_n \leq T$.*

However, this lemma turns out only necessary but not sufficient. It can be further refined. Observe that, if we remove some user nodes from a feasible system, resulting in a system that only consists of a subset of clients of the original one, the resulting system must also be feasible. Thus, by letting I_S denote the long-term average number of idle time slots in an interval when only a subset $S \subseteq \{1,2,...,N\}$ of clients is present, we obtain an even more stringent necessary condition.

Lemma 3 *A set of N clients is feasible only if $\sum_{n \subseteq S} w_n \leq T - I_S, forall S \subseteq \{1,2,...,N\}$.*

In that in this DH-MAC model, we don't use the simplest *first come first served scheduling policies*. Instead we use the *largest debt first scheduling policies*, for these scheduling policies are feasibility optimal, that can be proved in [2].

As a matter of fact, there are two different largest debt first scheduling policies. They differ in their definitions of debt. The first kind of debt, the time-based debt, is derived from the concept of load w_n defined in Lemma 1.

Definition 4 *Let $u_n(k)$ be the number of time slots that the AP spends in transmitting packet for client n in the k^{th} interval. The time-based debt of client n at the beginning of the $(k+1)^{th}$ interval is defined as $r^{(1)}(k+1) := kw_n - \sum_{j=1}^{k} u_n(j)$. The largest debt first policy that employs the time-based debt is called the largest time-based debt first scheduling policy.*

The second kind of debt, the weighted-delivery debt, is derived directly from the timely-throughput requirement q_n of a client.

Definition 5 *Let $d_n(k)$ be the indicator function of the event that the AP delivers a packet for client n in the k^{th} interval. The weighted-delivery debt of client n at the beginning of the $(k+1)^{th}$ interval is defined as $r^{(2)}(k+1) := \frac{kq_n - \sum_{j=1}^{k} d_n(j)}{p_n}$. The largest debt first policy that prioritizes according to the weighted-delivery debt is called the largest weighted-delivery debt first scheduling policy.*

Both largest debt first scheduling policies can be proved feasibility optimal, based on the Blackwell's approachability theorem [12]. And P.R.Kumar in [2] has got the result that the largest weighted-delivery debt first policy has a better performance over the largest time-based debt first policy since it converges faster. So we use the largest weighted-delivery debt first scheduling policy to determine the transmission order in the transmission queue.

B. Efficiency

As mentioned in the section III, there are two states of transmission. One is the normal state of transmission. The other is the abnormal state of transmission. In the different states of time slot, there are different efficiencies.

First, let us consider the normal state. The normal state of a time slot can be shown as Fig. 10. In the beginning of this time slot, there are two short parts, respectively AP sending CTS signal and WakeUp Signal. And after these parts, it is the main data transmission part. So the efficiency in the normal state, also called $Efficiency_1$, can be expressed as following:

$$Efficiency_1 = \frac{T_{data}}{T_{CTS} + T_{WakeUp} + T_{data}}$$

Fig. 10. A time slot in the normal state.

Second, then we talk about the abnormal state. The abnormal state, as mentioned above, means that the transmitting node finishes their transmission ahead of time, as shown in the Fig. 11. And the transmission is finished when the current time slot is not finished yet. And in this way there are additional two parts after the data transmission part, respectively user nodes sending Finish signal and AP sending Next signal. So the efficiency in the abnormal state, also called $Efficiency_2$, can be expressed as following:

$$Efficiency_2 = \frac{T_{data}}{T_{CTS} + T_{WakeUp} + T_{data} + T_{Finish} + T_{Next}}$$

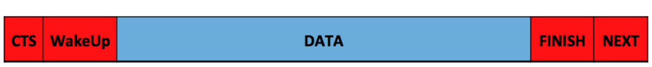

Fig. 11. A time slot in the abnormal state.

Then we have a definition, $P(n_i)$, as following:

Definition 6 *The possibility, $P(n_i)$, means that the ratio of the number of user node who has not yet finished their transmission in this time slot and the number of all user nodes in this time slot. Thus, $1 - P(n_i)$ means that ratio of the number of user nodes who has finished their transmission and the number of all user nodes in this time slot.*

From the above definition, we can see it that if the number of normally finished nodes increases, given a certain length of time period, the possibility, $P(n_i)$ increases too. Otherwise, the possibility, $1 - P(n_i)$ increases.

Therefore, with the Eff_1 and Eff_2, we can calculate the efficiency in one time period as following:

$$Efficiency = \frac{Sum\_of\_Eff_1 + Sum\_of\_Eff_2}{\sum_{i=1}^{N} n_i}$$

$$Sum\_of\_Eff_1 = \sum_{i=1}^{N} \{n_i \times P(n_i) \times Eff_1\}$$

$$Sum\_of\_Eff_2 = \sum_{i=1}^{N} \{n_i \times (1 - P(n_i)) \times Eff_2\}$$

C. Energy Consumption

In this subsection of Energy Consumption, we only take the situation of normal state into consideration, because both states have the very similar conditions of energy consumption. First we can see the energy consumption of a time slot. The Fig. 11 shows the energy consumption parts in a normal-state time slot. There are totally three main parts of energy consumption.

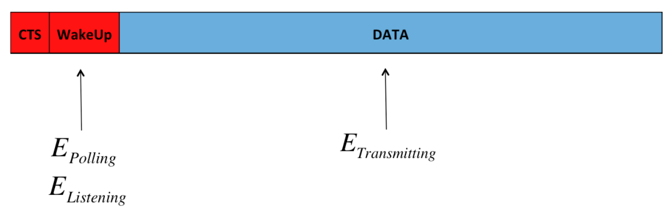

Fig. 12. Energy consumption in a time slot of normal state.

One major part is the data transmission, which is the useful part. And other two parts are respectively the polling part and the listening part, which are the useless parts. The polling part is that the transmitting user node spends energy in polling to wait for the WakeUp signal. In that this process is in the sleep mode of user node, it only costs a very small amount of energy. And the listening part is that transmitting user nodes spend at most a time slot listening to the channel, waiting for the CTS signal to start their transmission. And in this way, the DH-MAC model has the energy consumption ratio, η, as following:

$$\eta_{hybrid} = \frac{E_{Transmission}}{E_{Transmission} + E_{Polling} + N \times E_{Listening}}$$

As the value of N is equal to 1, this part of energy, $N \times E_{Listening}$, is also a small part of energy. So we can see that the DH-MAC model still has a relatively high energy consumption ratio.

Then we can compare the hybrid model with the TDMA model and the CSMA/CA model. In the TDMA model, we can see the energy consumption ratio is a simple ratio:

$$\eta_{TDMA} \approx \frac{E_{Transmission}}{E_{Transmission}} = 1$$

Also, we can get the energy consumption ratio with an additional energy consumption part, $E_{back-off}$:

$$\eta_{CSMA} = \frac{E_{Transmission}}{E_{Transmission} + E_{Listening} + E_{back-off}}$$

From above calculation of energy consumption ratio of three different models, we can have a comparison among the three models. In the comparison among the models, we can see the TDMA model has the best performance in that it don't use other jobs to schedule the transmission. Yet the CSMA model has a much worse performance, due to its large amount of energy wasted in the listening to the channel and process of back-off. And we can see our DH-MAC model has a relatively high energy consumption ratio, in that it uses only a small amount of energy to schedule and reversely gets a high performance of efficiency. The relationship among the three models is shown as following:

$$\eta_{TDMA} > \eta_{hybrid} >> \eta_{CSMA}$$

The analysis of energy consumption ratio can say that the dynamic hybrid model has three major advantages: (i) the DH-MAC model has a feasibility-optimal transmission order in the transmission queue; (ii) it also has a relatively high efficiency without the influence of the number of transmitting nodes; (iii) this hybrid model has a high energy consumption ratio, close to the TDMA model.

V. Simulation

In the simulation section, we have finished two different parts of simulation. The first part is about the relationship between the current number of transmitting nodes and the current length of time period. Because in our DH-MAC model, the closely linear relationship between these two values is a important basement, only if this condition is satisfied, all the assumptions can be possible. And then the second part is about an important standard to evaluate a MAC protocol, which is the efficiency. Only when our DH-MAC model can achieve higher efficiency than the other two models, we can get it that this DH-MAC model is better than others.

A. Parameters Setting

We use both the GCC compiler and Matlab to get the simulation results. We follow the G.711 codec, which is a ITU-T standard for audio compression, in deciding parameters for traffic with QoS constraints. G.711 generates data at 64 kbps. With a 20 ms packetization interval, this results in a 160 Bytes VoIP packet. We use IEEE 802.11b as the underlying MAC protocol, whose transmission rate can be as high as 11 Mb/s. All the parameters are set as Fig. 13.

And then we set the number of user nodes from 100 to 1000 with the step of 10. The arrival time of user nodes follows the random distribution from 0 to a upper bound of arrival time, called as MAXtime. The data packet of user nodes also follows the random distribution from 0 to another upper bound, called as MAXpacket. And in every process of simulation, the total number of user nodes is a constant value. It only varies when the system is reset.

Packetization interval	20 *ms*
Payload size per packet	160 Bytes
Transmission data rate	11 Mb/s
SIFS	10 μs
PIFS	30 μs
DIFS	40 μs

Fig. 13. Parameters setting table.

B. CurNodeNum vs. CurTimeLength

As mentioned above, the closely relative function of the current number of transmitting nodes and the current length of time period is the basement of the DH-MAC model. So we first make two curves showing the trends of two values. In the every process of simulation, we record the number of transmitting nodes and the length of time period in every time period. Then we make the curves with the according values and the serial number of time period. Thus, we can get the curves like Fig. 14 and Fig. 15.

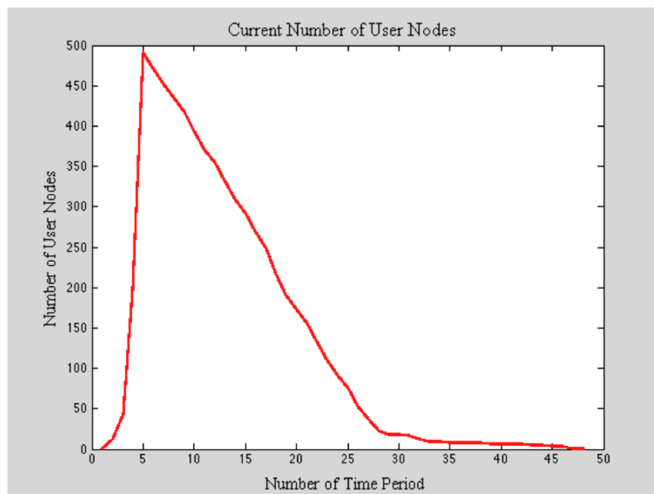

Fig. 14. The number of transmitting nodes in one process.

From the above two curves, we can see that the user nodes arrive in the system from the time of 0 to the MAXtime. And during this range of time, the number of transmitting nodes has the trend of increment. Also, after this MAXtime, the number decreases with more and more user nodes finishing their transmission. This trend fits for the actual conditions. Then let us see another curve between the length of time period and time. We can also find the trend of this curve follows the other curve. So we can say that the two curves are highly related with each other and the basement of the DH-MAC model is satisfied.

C. Efficiency

Efficiency is the most important advantage of our DH-MAC model. The DH-MAC model can achieve a relatively constant

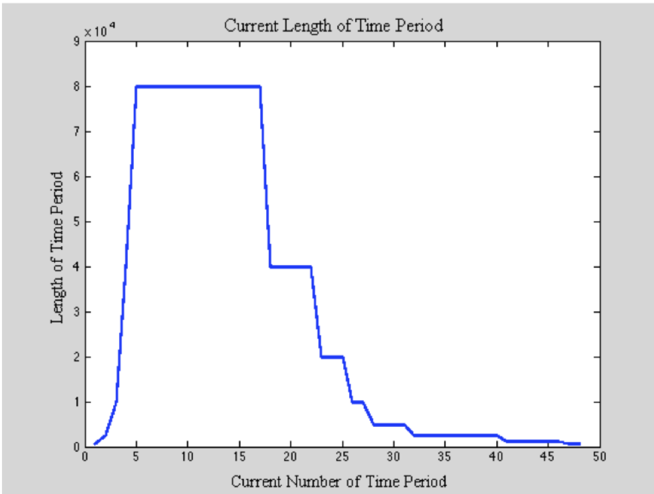

Fig. 15. The length of time period in the same process.

efficiency in that the length of time period can vary with the change of the number of transmitting nodes. So in this way the ratio of length of time period and the number of transmitting nodes is a relatively constant value. That makes the system can perform statically. And the Fig. 16 shows the efficiencies among the hybrid model, the TDMA model and the CSMA/CA model.

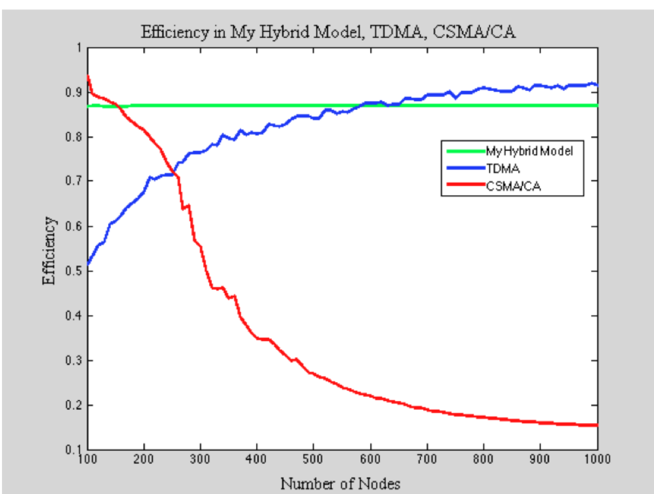

Fig. 16. The efficiencies comparison among the hybrid model, TDMA model and CSMA/CA model.

In Fig. 16, we can see three different curves. The green one is our DH-MAC. We can easily see it that the green one has a relatively constant efficiency with the variation of number of user nodes. And also it's a relatively high efficiency. In addition, the red one is referred to CSMA/CA model. The CSMA/CA model has a little higher efficiency when the number of user nodes is small enough, because of no collisions. However, with the increment of number of user nodes, the efficiency of CSMA/CA model decreases in a great degree. Also, the blue one is the TDMA model. Similarly, the TDMA model has a comparatively low efficiency when the number of user nodes is small. Thus, if we consider the average efficiency, the DH-MAC model has the overwhelming advantage over the other two models. In this way we can say that the DH-MAC model is much better and stable than the other two models.

VI. Conclusion

This paper designs a dynamic hybrid MAC protocol, DH-MAC, with the mechanisms of TDMA and CSMA/CA. Unlike other hybrid models of TDMA and CSMA/CA, this DH-MAC maximizes the advantages and minimizes the disadvantages of both models. The DH-MAC model adds the mechanisms of CSMA/CA into the TDMA model and then optimizes the dynamic TDMA model in a further step. Then it has a relatively stable and constant relationship between the current number of transmitting nodes and the length of time period. In this way the DH-MAC model can achieve a high efficiency all the time, no matter what the number of user nodes is. And the conclusion can get conformed with help of simulations on GCC compiler and Matlab.

What's more, there is also an important part of this paper. In the scheduling part of this hybrid model, we don't just use the first-in first-served policy. But we use a much more complicated model called the largest debt first scheduling policies. In these policies, there are two different kinds of debts, the time-based debt and the weighed-delivery debt. Both largest debt first scheduling policies can be proved feasibility optimal. And the largest weighted-delivery debt first scheduling policy has a better performance than the other one. Thus the DH-MAC model uses the largest weighted-delivery debt first scheduling policy to determine the transmission order in the transmission queue.

VII. Future Work

In the future, we will focus on the three works. The first one is that we can have a lot more to improve the system model. Because every MAC protocol has its own flaws, including our DH-MAC model, we need to keep improving our hybrid MAC protocol and add new theories in it. The second job is that we can still use other more professional tools, like Ns-2 or Ns-3, to simulate our system model, in that the GCC compiler and the Matlab are not enough obviously. The third work is most important. After all, we design a MAC protocol. If we don't implement the DH-MAC model in the real-time system, we will never know whether it is a good one or not. So if possible, we can implement our hybrid MAC model into the free BSD systems or MIMO systems to see whether it still can achieve high performance as simulation.

References

[1] Cisco. Cisco visual networking index: Global mobile data traffic forecast update, 2011-2016. 2012.

[2] I-Hong Hou, P.R.Kumar. Performance Analysis of the IEEE 802.11 Distributed Coordination Function. Morgan&Claypool Publisher. 2013.

[3] Bianchi G. Performance analysis of the IEEE 802.11 distributed coordination function[J]. Selected Areas in Communications, IEEE Journal on, 2000, 18(3): 535-547.

[4] Gong H, Liu M, Yu L, et al. An event driven TDMA protocol for wireless sensor networks[C]//Communications and Mobile Computing, 2009. CMC'09. WRI International Conference on. IEEE, 2009, 2: 132-136.
[5] Rhee I, Warrier A, Aia M, et al. Z-MAC: a hybrid MAC for wireless sensor networks. IEEE/ACM Transactions on Networking (TON), 2008, 16(3): 511-524.
[6] Shrestha B, Hossain E, Choi K W. Distributed and Centralized Hybrid CSMA/CA-TDMA Schemes for Single-Hop Wireless Networks[J]. arXiv preprint arXiv:1401.5528, 2014.
[7] W. Ye, J. Heidemann, and D. Estrin. Medium access control with coordinated adaptive sleeping for wireless sensor networks. IEEE/ACM Trans. Netw. vol. 12, no. 3. pp. 493-506. Jun. 2004.
[8] T. van Dam and K. Langendoen. An adaptive energy-efficient mac protocol for wireless sensor networks. in Proc. ACM SenSys, New York, 2003. pp. 171-180.
[9] J. Polastre, J. Hill, and D. Culler. Versatile low power media access for wireless sensor networks. in Proc. ACM SenSys, New York, 2004, pp. 95-107.
[10] J. Hill and D. Culler. A wireless embedded sensor architecture for system-level optimization. Univ. California, Berkeley, Tech. Rep. 2001.
[11] Y. Tay, K. Jamieson, and H. Balakrishnan. Collision-minimizing CSMA and its applications to wireless sensor networks. IEEE J. Sel. Areas Commun. vol. 22, no. 6. pp. 1048?1057. Aug. 2004.
[12] D. Blackwell. An analog of the minimax theorem for vector payoffs. Pacific J. Math. vol. 6, no. 1. 1956.
[13] Shi L, Fapojuwo A. TDMA scheduling with optimized energy efficiency and minimum delay in clustered wireless sensor networks[J]. Mobile Computing, IEEE Transactions on, 2010, 9(7): 927-940.
[14] Wang Y, Shi P, Li K, et al. D-TDMA: An approach of dynamic TDMA scheduling for target tracking in wireless sensor networks. Green Computing and Communications (GreenCom), 2010 IEEE/ACM Int'l Conference on & Int'l Conference on Cyber, Physical and Social Computing (CPSCom). IEEE, 2010: 546-553.
[15] Omar H A, Zhuang W, Li L. VeMAC: A TDMA-based MAC protocol for reliable broadcast in VANETs[J]. Mobile Computing, IEEE Transactions on, 2013, 12(9): 1724-1736.
[16] Ma J, Lou W, Wu Y, et al. Energy efficient TDMA sleep scheduling in wireless sensor networks[C]//INFOCOM 2009, IEEE. IEEE, 2009: 630-638.
[17] Rhee I, Warrier A, Min J, et al. DRAND: distributed randomized TDMA scheduling for wireless ad-hoc networks[C]//Proceedings of the 7th ACM international symposium on Mobile ad hoc networking and computing. ACM, 2006: 190-201.