Neighbor-Aware Multiple Access Protocol for 5G mMTC Applications

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Abstract: In order to support massive Machine Type Communication (mMTC) applications in future Fifth Generation (5G) systems, a key technical challenge is to design a highly effective multiple access protocol for massive connection requests and huge traffic load from all kinds of smart devices, e.g. bike, watch, phone, ring, glasses, shoes, etc.. To solve this hard problem in distributed scenarios with massive competing devices, this paper proposes and evaluates a Neighbor-Aware Multiple Access (NAMA) protocol, which is scalable and adaptive to different connectivity size and traffic load. By exploiting acknowledgement signals broadcasted from the neighboring devices with successful packet transmissions, NAMA is able to turn itself from a contention-based random access protocol to become a contention-free deterministic access protocol with particular transmission schedules for all neighboring devices after a short transition period. The performance of NAMA is fully evaluated from random state to deterministic state through extensive computer simulations under different network sizes and Contention Window (CW) settings. Compared with traditional IEEE 802.11 Distributed Coordination Function (DCF), for a crowded network with 50 devices, NAMA can greatly improve system throughput and energy efficiency by more than 110% and 210%, respectively, while reducing average access delay by 53% in the deterministic state.

Keywords: neighbor-aware multiple access; contention-based random access; contention-free deterministic access; ACK signal; 802.11 DCF

I. INTRODUCTION

The Fifth Generation (5G) wireless communication system is promising and significant in communications area. International Telecommunication Union (ITU) has defined three main applications in 5G, which are Enhanced Mobile Broadband, massive Machine Type Communications (mMTC) and Ultra-reliable and Low Latency Communications. It is expected that 5G communication systems should be at least 1000 times in capacity, and 10 to 100 times in traffic connectivity when compared with legacy 4G system. Although evolution of 4G with some key technologies has shown to be with higher capacity and larger transmission data rate, it cannot fully fulfill the requirements for 5G communications. To this end, many new multiple access technologies have been proposed recently, e.g., non-orthogonal multiple access (NOMA) [1], Multi-User Shared Access (MUSA) [2] and Sparse Code Multiple Access (SCMA) [3]. 5G mMTC [4] also faces the challenges of massive connectivity and huge traffic load requirements. It should support massive number of all kinds of smart devices, e.g. bike, watch, phone, ring, glasses, shoes, etc.. Meanwhile, most mMTC devices are generally equipped with low-volume batteries and are expected to operate for a long time without the need to replace batteries. As a result, very low power consumption is vital for the operations, which means high energy efficiency is an essential.

Contention-based random access is a typical scenario of mMTC. Wireless Local Area Network (WLAN) and wireless sensor networks are two typical contention-based networks. For future 5G system, 802.11ah and the Internet of Things (IoT) also bring requirements of larger connection number of devices per receiver, e.g., access point, sink, etc.. In a contention-based network, Carrier Sense Multiple Access (CSMA) is a widely applied approach, in which stations will sense the channel before starting a transmission. The well-known 802.11 Distributed Coordination Function (DCF) [5] is based on CSMA with Collision Avoidance (CSMA/CA). In 802.11 DCF, the most popular random access protocol is Binary Exponential Backoff (BEB). BEB is easy to be realized. However its performance is far from optimum [6], especially for a network with high traffic load [7]. Many researchers made great efforts to improve the performance of random access networks. In [7–9], Multiplicative Increase and Linear Decrease (MILD), Double Increment Double Decrement (DIDD), Linear/Multiplicative Increase and Linear Decrease (LMILD) were proposed respectively. All of them tried to reduce packet collisions by making some techniques on adjusting the CW sizes. Yang proposed a new Double Sense Multiple Access (DSMA) protocol in [10] to solve the hidden terminal problem in random access systems. In [11], Busy Tone based cooperative medium Access Control (BTAC) protocol was set up to improve the connectivity in random access networks, thus enhancing the system performance.

The protocols above are all random access algorithms, while some new access protocols which are semi-deterministic are also set up. They combine both random and deterministic processes. In [12–14], Learning-BEB (L-BEB), E2CA and Semi-Random Backoff (SRB) protocols were put forward respectively. They utilized some smart methods to turn the random access network to be semi-deterministic, hence system performances were improved to a great extent.

However, all of the prior access protocols cannot fulfill the massive connectivity and huge traffic load requirements of 5G mMTC. Thus to solve this hard problem in distributed scenarios with massive competing devices, in this paper, we propose a novel Neighbor-Aware Multiple Access (NAMA) protocol. By exploiting acknowledgement signals broadcasted from the neighboring devices with successful packet transmissions, each device's transmitting order is clarified. Then NAMA can convert itself from a contention-based random access protocol to a contention-free deterministic access protocol with particular transmission schedules for all neighboring devices after a short transition period. Moreover, NAMA has characteristics of neighbor-awareness and adaptiveness. Extensive simulations are conducted and results show that the good performance of NAMA in terms of transition delay, throughput, access delay and energy efficiency. When all the devices' access processes are deterministic, the whole system would turn to be TDMA, so that collisions are avoided. And thus fairness can also be guaranteed. The approach is easy to be implemented, which makes tiny modification to the existing protocol. Therefore, it is very suitable for mMTC scenario with massive devices.

The rest of the paper is organized as follows. In Section II, the system model is presented. In Section III, the NAMA protocol is proposed in details. Extensive numerical results are shown in Section IV. We conclude the work in Section V.

II. SYSTEM MODEL

In a mMTC contention-based network, as shown in Fig. 1, devices are randomly distributed, and connected to the same receiver. Similar to [9, 12, 15], all devices are in the transmission range of each other. Each device keeps on sensing the channel, and then makes decisions on whether and when to transmit. The basic random access process is as follows. A device senses the channel, if the channel is free for a period of Distributed Inter-Frame Spacing (DIFS), and at the same time the device has a packet to transmit, then it backoffs for some slots according to a certain protocol. When backoff process ends, and at the same time the channel is still idle, it transmits. Otherwise it waits till the channel is free again, and repeats the process aforesaid. If the receiver successfully receives a packet, it will broadcast an ACKnowledgement (ACK) signal to the network. ACK signal contains MAC address, hence all the devices can analyze the ACK signal to know who has had this successful transmission. If the transmission fails due to collisions, the receiver sends nothing back, but a device will know the failure after a certain number of slots without receiving an ACK, and then start a retransmission process.

The network consists of one receiver and N devices. It operates under a saturation condition, so every device has a queue of packets to send all the time. Besides, the channel is assumed to be ideal, so that packet transmission failure is only caused by collisions. In order to ensure fairness, there is no priority among all the devices and packets.

III. NEIGHBOR-AWARE MULTIPLE ACCESS

Before detailed introduction on NAMA protocol, some terms are defined as follows.

Random access group: Devices in random state that performs legacy 802.11 DCF make up the random access group. All devices are in the random access group at the beginning.

Deterministic access group: When a device in the random access group has a successful transmission, it turns into the deterministic access group.

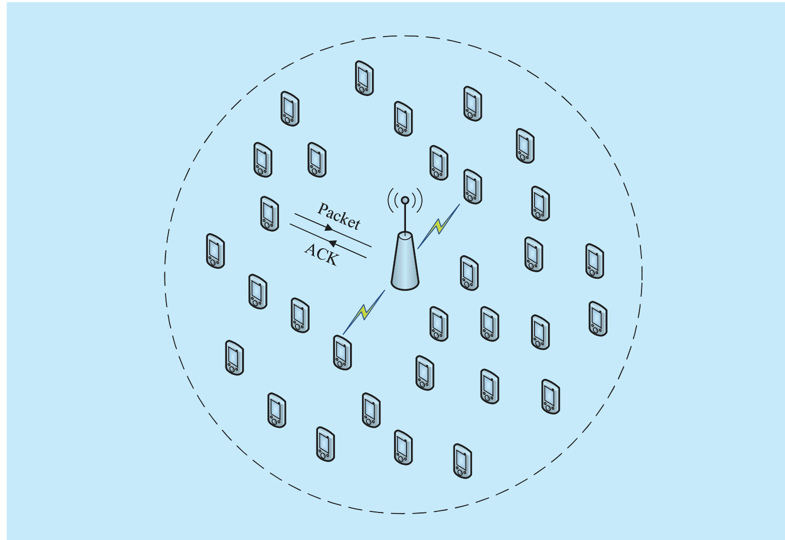

Fig.1 *A typical contention-based network.*

Slot group: In the random access process, when a new device in the system successfully transmits a packet, the whole system would start a new access process immediately. Then devices that enter the deterministic access group will transmit packets in order according to the NAMA protocol we are about to propose below. After all the devices in the deterministic access group transmitting packets, those that are still in random access group start competing for the channel, until another successful transmission. The period between the time a new access process starts and the next successful transmission by a new device is called a slot group. As shown in Fig. 2, every solid line represents the time of starting a new access process. The slots between two neighboring solid lines constitute a slot group. Note that the slot group size is not a constant.

The first part of NAMA is the ACK counter value updating process shown in Algorithm 1-Part I. Devices counts ACK signals from successful transmitted neighboring devices. The core idea is described as follows. Let A_i be the value in the ACK counter of Device i ($i \in \{1,2,...,N\}$). If Device i receives its own ACK signal, A_i resets to be 0. If Device i receives Device j's ($j \neq i, j \in \{1,2,...,N\}$)

ACK signal for the first time after a successful transmission, A_i increases by 1. If Device i receives Device j's for the second or more times after its last successful transmission, A_i remains the same.

After a period of time, the values of ACK counters in different devices will become totally different. In Fig. 2, an example of a four-device network is shown to see how A_i changes. In Slot group 2, Device A transmits a packet and its ACK counter value becomes 0. Next, Device B has a successful transmission. So ACK counter values become 1 and 0 for Device A and B. In Slot group 3, Device B has a transmission. Since it is the second time for Device A hearing Device B's successful transmission after Device A's last successful transmission, the ACK value of Device A remains to be 1. We see that when all devices have successfully sent a packet, Devices A, B, C and D's ACK counter values become different, varying from 0 to 3 (We can further show that if there are N devices, A_i would vary from 0 to N − 1). Also, A_i will vary constantly and adaptively according to the ACK information collected. In the same slot, ACK counter values are all different from each other, which can be applied to determine the transmitting order. Actually, the ACK number counting process explores the relationship among devices. So every device could know the sending information from neighbors, that is to say, they are *neighbor-aware*.

Next, we come to the second part of NAMA, the algorithm for the network turning from totally random access to totally deterministic access. The algorithm is shown in Algorithm 1-Part II.

Detailed processes are depicted below.

● At the beginning, the whole system is initialized.

● All the devices compete for the channel according to BEB protocol, until one of them occupies the channel and successfully transmits a packet. The successful transmitted device enters deterministic state. Then the receiver tells all the devices that the system would go into the next slot group. In the meanwhile, all the devices would count the ACK number according to the ACK counting algorithm of NAMA.

● In a new slot group, devices in the deterministic access group would transmit packets in order. One can only transmit one packet at a time. After all the devices in deterministic access group finish their transmission, those that remain in the random access group begin to compete for the channel again, until a new successful transmission.

● Repeat steps above, till all the devices

Algorithm 1 Neighbor-Aware Multiple Access

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Input: Random access group R, deterministic access group D, A_i
Part I: The process of updating A_i
1: if Device i successfully transmits a packet then
2:     A_i ← 0
3: end if
/*After Device i's last successful transmission*/
4: while Device i has no packet to transmit or is waiting do
5:     if Device j ( j ≠ i ) successfully transmits a packet for the 1st time then
6:         A_i ← A_i + 1
7:     else {Device j ( j ≠ i ) successfully transmits a packet for the 2nd or more time}
8:         A_i ← A_i
9:     end if
10: end while

Part II: Transmission in the transition period and deterministic state.
11: if Device i ∈ R then
12:     Perform BEB protocol
13:     if Device i has a successful transmission then
14:         Update A_i according to Algorithm 1-Part I
15:         D ← D ∪ i, R ← R \ i
16:         Device i enters the next slot group
17:         Transmit in the A_i-th slot
18:     else {Device j ( j ≠ i ) ∈ R has a successful transmission}
19:         Device i enters the next slot group
20:         Wait until all devices in D finish transmission
21:         Perform BEB protocol
22:         Goto Line 13
23:     end if
24: else {Device i ∈ D}
25:     Update A_i according to Algorithm 1-Part I
26:     Transmit in the A_i-th slot in the next slot group
27: end if
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enter the deterministic access group.

In Fig. 2, small rectangles represent ACK signal. And every blank slot represents the slot in which devices that are in random access states are competing for the shared channel. White regions indicate the transition period and grey regions the deterministic state. For devices in the deterministic access group, the transmission order in every slot group is described as follows. For every slot group, slots are numbered beginning with 0. At the end of the last slot group, devices in the deterministic access group would have different A_i values. Then in the new slot group, devices in the deterministic access group will transmit according to their own A_i. For example, in Fig. 2, we see that at the end of Slot group 3, ACK counter values of Devices A, B and D are 1, 2 and 0 respectively. So in the beginning of Slot group 4, the transmission order is D, A, B.

From the algorithm above, we know that in a certain slot group, there is one and only one device that will turn into deterministic access state. So gradually, all the devices would join the deterministic access group one by one. However, in the real situation, receiver and devices in the system don't know the exact number of devices in the network. After all devices go into the deterministic access group, according to the protocol above, all the devices will wait for another successful transmission by a device in the random access state, which is impossible. Then the whole system will come into an endless waiting pattern. To avoid this phenomenon, we supplement such a rule, that if devices don't detect anything happening in the system in CW_{min} slots from each other, they know that all of them have entered the deterministic access state, and move to the next slot group. From then on, the whole network enters the deterministic state. Henceforth devices can transmit packets in order.

IV. Numerical Results

Simulation parameters are shown in Table I. The basic mode of legacy 802.11 DCF is employed. Note that we separate random state

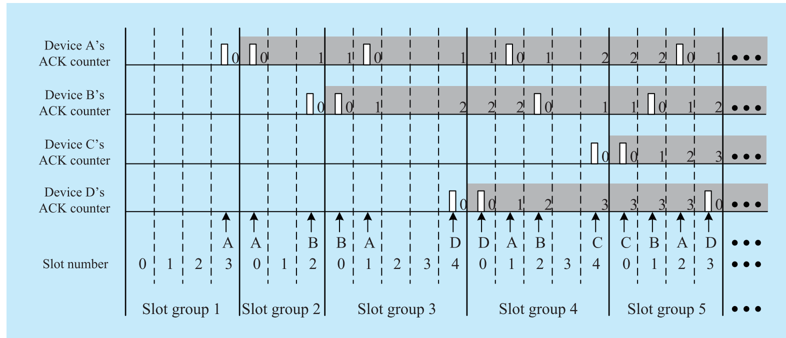


Fig.2 *The transition period from contention-based random access to contention-free deterministic access in a four-device network.*

and transition period with the deterministic state. Performances of random state and transition period are displayed in "Random State and Transition Period" part so as to survey the converting trend of NAMA. While when compared with legacy 802.11 DCF, performances in the deterministic state are adopted.

4.1 Random state and transition period

The process that the network turns from a totally random access state into a totally deterministic access state is defined as the transition period. The time duration for transition period is defined as transition delay which represents the convergence rate of the system.

4.1.1 Transition delay

The result of transition delay is shown in Fig. 3-(a). We can see that as the number of devices

Table I *Simulation parameters*

Parameters	Value
Packet size	8184 bits
MAC header	272 bits
PHY header	128 bits
ACK	112 bits + PHY header
Channel bit rate	1 Mb/s
Slot time	50 µs
SIFS	28 µs
DIFS	128 µs
ACK timeout	300 µs
CWmax	1024
Transmitting power	1.5W
Receiving power	1.0W
Sensing power	0.5W

increases, gradient of the curve for transition delay of the system increases, which is quite reasonable. The more devices the system has, the more conflicts and retransmissions, so the longer of the transition delay.

The transition delay when $CW_{min} = 16$ is the longest while that of when $CW_{min} = 64$ shortest. It is because that when CW_{min} is small, more collisions will occur in the transition period. However, we should notice that the difference among the three transition delay curves is very small. For a 5-device network system, the transition delay is about 0.14s according to our simulation result, and for a 25-device network, it is about 3.1s, while a 50-device network needs about 12.0s. So just after 12s, a 50-device network system can get to the confliction-free state, which is quite fast.

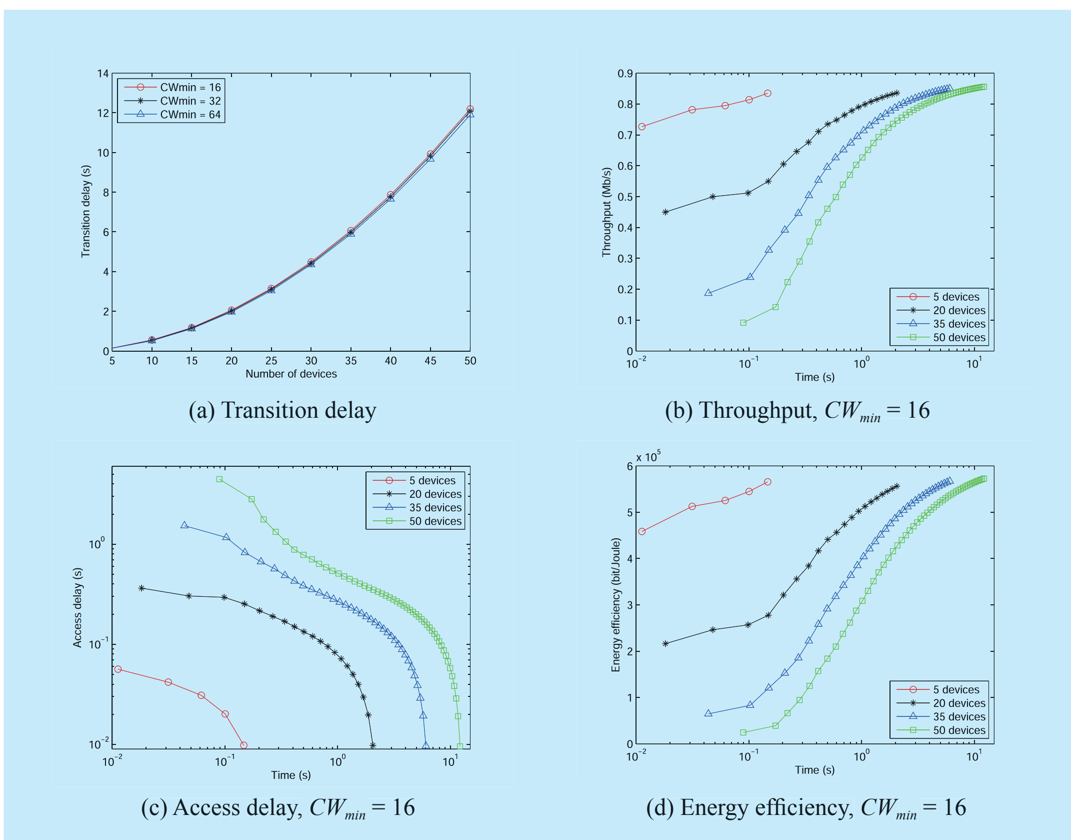
4.1.2 Throughput

Throughput is an important metric for a network. It is defined to be the fraction of time the channel is used to successfully transmit payload bits [5].

Seen from Fig. 3-(b), when the system has different number of devices, their system throughput all go higher in the transition period. It is because that the system is changing to be a deterministic access network as time goes on. As the number of devices increases, the initial values of throughput decrease as a result of more collisions. The value on x-axis of the first point of each curve is the time that the network has the first successful transmission. We can also find that with the number of devices increasing, the time of the first successful transmission postpones, which also results from more collisions.

4.1.3 Access delay

Low latency is of great significance in 5G communication systems, which is an essential metric to evaluate a new protocol. The average access delay is defined to be the time



(a) Transition delay

(b) Throughput, $CW_{min} = 16$

(c) Access delay, $CW_{min} = 16$

(d) Energy efficiency, $CW_{min} = 16$

Fig.3 *Transition delay, throughput, access delay and energy efficiency of NAMA in transition period,* $CW_{max} = 1024$

consumed between the moment that the packet becomes the head-of-line (HOL) one and the moment that the packet ends a successful transmission.

From Fig. 3-(c), when the system has different number of devices, access delays all decrease in the transition period, which is also caused by the tendency that the system is changing to be a deterministic access network step by step. Initial values of access delays increase as a result of more collisions when the number of devices gets bigger.

4.1.4 Energy efficiency

When designing a new protocol, not only are high throughput and low latency considered, but also it should be more energy efficient. Energy efficiency is also of great necessity in 5G communication systems [16]. In this paper, energy efficiency is defined as the successful transmitted payload bits per Joule .

From Fig. 3-(d), in the transition period, energy efficiencies all become larger for the four curves, since the system is converting to be a deterministic access network gradually. Other results are similar to those in the "Throughput" part above.

4.2 Deterministic state

4.2.1 Throughput

We show the result of our new NAMA protocol compared with legacy 802.11 DCF with BEB algorithm in Fig. 4-(a). Under the saturation scenario, when the system gets to the deterministic access state using NAMA protocol, since in every slot there would be a successful transmission, the throughput is a constant number. And it is regardless of the number of devices. But for legacy 802.11 DCF, as the number of devices increases, the collision rate will grow, so that the system throughput decreases. For a network with 25 devices, NAMA can greatly improve system throughput by 58% in the deterministic state, compared with legacy 802.11 DCF. While with 50 devices, NAMA largely outperforms legacy 802.11 DCF by 110% in throughput.

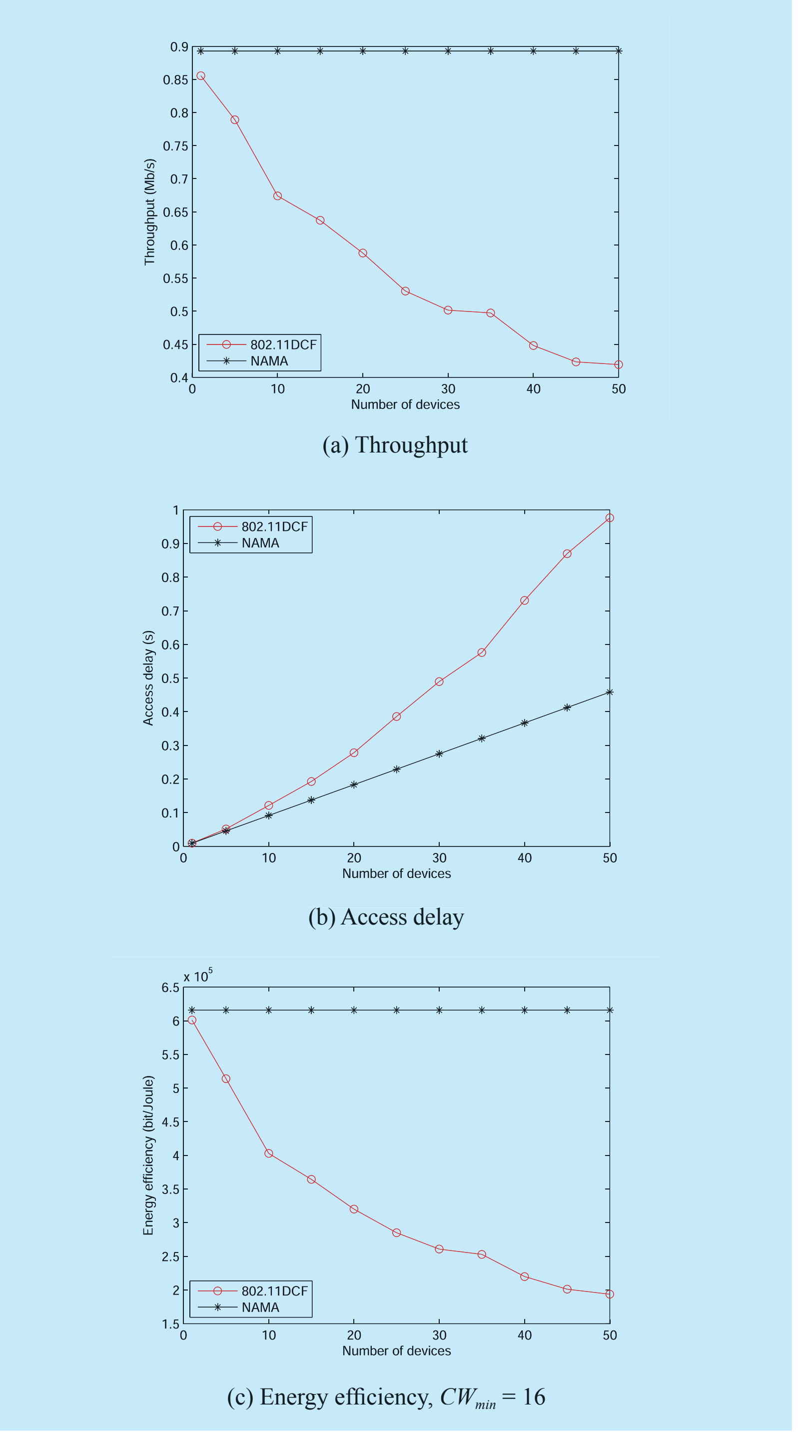


Fig.4 *Throughput, access delay and energy efficiency of NAMA in deterministic state,* $CW_{min} = 16$, $CW_{max} = 1024$.

4.2.2 Access delay

From Fig. 4-(b), as the number of competing devices increases, gradient of the average access delay curve for legacy 802.11 DCF goes higher, resulting from more collisions in the system. While for NAMA, there is a packet to transmit without conflict in every slot, so that the average access delay increases linearly. When the system has 25 devices, NAMA can reduce the average access delay by 40% compared with legacy 802.11 DCF, while with 50 devices it can reduce highly up to 53%. Again, it proves the high efficiency of NAMA.

4.2.3 Energy efficiency

Simulation result of energy efficiency is shown in Fig. 4-(c). From the results we see that when the system gets to the deterministic access state using NAMA protocol, the energy efficiency is a constant number, because of NAMA's collision-free property. And it is better than that of legacy 802.11 DCF. For a network with 25 devices, NAMA can hugely enhance energy efficiency by 116% in the deterministic state, compared with legacy 802.11 DCF. And for a 50-device network, it can improve the energy efficiency as high as 210%.

V. Conclusions and Future Work

The mMTC applications in future 5G systems are challenging with the key requests of massive connectivity and huge traffic load. In order to support mMTC applications, in this paper, we proposed a novel Neighbor-Aware Multiple Access (NAMA) protocol. By exploiting ACK signals of neighboring devices, packets are transmitted in a designed order according to the number of ACK signals. And then NAMA can convert itself from a contention-based random access protocol to a contention-free deterministic access protocol with particular transmission schedules for all neighboring devices after a short transition period. Extensive simulations are conducted under different network sizes and CW settings, which verify the effectiveness of NAMA in terms of transition delay. For a crowded network with 50 devices, its performance outstrip legacy 802.11 DCF in system throughput, average access delay and energy efficiency largely.

In the future, hidden terminal problem will be further researched. Meanwhile, devices' adding in and exiting process will be studied. Moreover, system performance under unsaturated scenario would also be studied.

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