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AFDA: Asynchronous Flipped Diversity ALOHA for Emerging Wireless Networks With Long and Heterogeneous Delay

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ABSTRACT The design of random media access control (MAC) protocol renews great attention for emerging challenged wireless environments, where the propagation delay is long, heterogeneous, and/or varying, such as satellite or underwater acoustic sensor networks. In these environments, the existing MAC solutions based on slotted transmissions, carrier sensing, or channel reservation by control packets are no longer favorable or even feasible. In this paper, we propose the asynchronous flipped diversity ALOHA (AFDA) to tackle the challenges based on a new diversity transmission scheme. Different from the existing diversity transmission schemes, each data packet and its flipped replica are transmitted back to back, and the zigzag decoding technique is adopted to resolve collisions. The performance of AFDA has been evaluated by analysis and simulations. The results show that, without time synchronization or handshaking requirements, the performance of AFDA is unaffected by the duration or variation of the propagation delay, and it substantially improves system performance in terms of throughput, packet loss ratio, and network admission region.

INDEX TERMS Flipped zigzag decoding, random access, ALOHA, long and heterogeneous propagation delay, wireless networks.

I. INTRODUCTION

Although the first random-access (RA) media access control (MAC) protocol, ALOHA, was proposed three decades ago, design of distributed RA MAC protocols remains an important issue, particularly for emerging challenged environments, such as the satellite or underwater acoustic sensor networks. In such environments, the new challenges are (a) the propagation delay can be significant or even much longer than the transmission delay; (b) the propagation delay is heterogeneous and/or varying, which may not only be different between different transmitter-receiver pairs but also change over time; and (c) some nodes are equipped with a transmitter only without the receiving capability to minimize the energy consumption. Given the above challenges, the existing RA solutions based on slotted transmissions, carrier sensing multiple access (CSMA), or channel reservation by control packets (*e.g.*, using ready-to-send or clear-to-send) are no longer favorable or feasible [2]–[5].

On the other hand, recent advances in signal processing shed new light on how to effectively decode collided packets [6]–[9] if the collisions follow certain patterns. Taking advantage of such signal processing technique, in this paper, we propose a distributed RA MAC protocol named Asynchronous Flipped Diversity ALOHA (AFDA).

The main contributions of this paper are two-fold. First, we propose the AFDA protocol which is designed for networks with long, heterogeneous, and/or varying propagation delay. AFDA combines a flipped diversity transmission scheme and the Zigzag decoding technique [9]. Different from the existing diversity transmission schemes [10]–[19], AFDA is a truly asynchronous MAC protocol requiring neither network-wide time synchronization nor the source nodes to have the receiving capability. Second, we investigate the performance of the proposed AFDA protocol by both analysis and extensive simulations. The results demonstrate the substantial performance gains of AFDA compared with the existing solutions in terms of throughput, packet loss ratio, and network admission region.

The rest of the paper is organized as follows. We discuss the related work in Section II. Section III presents the system model. The AFDA protocol is described in detail in Section IV. The performance bounds of AFDA are derived in Section V. Simulation results are given in Section VI, followed by concluding remarks and future research issues in Section VII.

II. RELATED WORK

For RA, since the maximum channel utilization for the (pure) ALOHA protocol is only 18% due to packet collisions, how to avoid or resolve collisions is critically important. Slotted ALOHA and schemes based on slotted ALOHA [4], [20] halves the collision probability in ALOHA by dividing time into synchronized slots. Carrier sensing and handshaking based schemes, such as CSMA [2], Distributed Coordination Function (DCF) in IEEE802.11 [21], MACA [22], Slotted FAMA [23], APCAP [24], and T-Lohi [25], reduce the collision probability by coordinating or negotiating among different transmitters. These solutions are preferable if the propagation delay is negligible. However, in emerging challenged environments, such condition is invalid. For example, the propagation delay can be up-to 250 ms in geostationary satellite networks due to the long distance from terrestrial terminals to communication satellites, and the delay in acoustic underwater networks is five-order of magnitude higher than that in over-the-air wireless networks. With lengthy propagation delay, CSMA-based techniques are no longer favourable [2] as their throughputs are bounded by the ratio between the propagation delay and the transmission delay [3]. Also, due to location-dependent heterogeneous propagation delay, the benefit of synchronization in slotted ALOHA disappears [4]. For negotiation or handshaking-based schemes strategies, they may be available for scenarios with heterogeneous and/or varying propagation delay. However, similar to CSMA-based techniques, they are inefficient when the duration of propagation is large. In addition, they typically require accurate locations of source nodes and global time synchronization, which are non-trivial for implementation or infeasible if the nodes have no receiving/sensing capability.

To improve the efficiency of RA, Diversity Slotted ALOHA (DSA) protocol was proposed [10] to enhance the RA channel capabilities, in which each packet is transmitted twice or more so as to decrease packet loss ratio caused by collisions. CRDSA [11] introduces iterative interference cancellation (IIC) and frame-structure (multiple slots in a frame) based media access to assist the collision resolution. In each frame, replicas of a packet are sent in randomly selected slots. When there are two replicas for each packets, CRDSA outperforms SA with the maximum throughput as 0.55 *packet/slot*. Following CRDSA, CRDSA++ considers more replicas (3 or 4) for each packet and the maximum throughput is further improved to be 0.68 *packet/slot*. Later on, a generalized CRDSA, the Irregular Random Slotted ALOHA (IRSA) was proposed in [12] to use random number of replicas for each packet according to a predefined distribution of the replicas' number. In [13], Coded Slotted ALOHA (CSA) further generalizes IRSA by considering the coding among the multiple replicas of a packet. As demonstrated in [12] and [13], the maximum throughput can be up to 0.97 *packet/slot*. [26] provided a comprehensive analytic framework able to assess the performance of a number of slotted access techniques from the more conventional SA and DSA to the more elaborated CRDSA in the presence of arbitrary traffic and power distribution and taking into account effective coding and modulation schemes adopted at physical layer. Other schemes similar to CRDSA, which exploit iterative cancellation in frame-based channel access include Multi-Slots Coded ALOHA (MuSCA) [14], enhanced MuSCA [15], and Pseudo-random ALOHA [16], [17]. In MuSCA, the coded symbols embedding Forward Error Correction (FEC) redundancy are spread across two or more bursts in the frame slots, which is similar to CSA. In [15], an irregular degree distribution of the MuSCA coding rates is applied to different packets. In Pseudo-random ALOHA, a node selects the slots in each frame for its packet replicas based on a deterministic pseudo random function of the message payload, which allows to perform cancellation of the received message from previous transmissions thus improving the throughput.

Note that, although CRDSA and other follow-on protocols can enhance throughput for networks with long propagation delay, they all rely on network wide synchronization at slot level, which makes them inapplicable in the emerging networks when the propagation delay is heterogeneous and/or varying.

Without requiring slot level synchronization, [18] proposed Contention Resolution ALOHA (CRA), in which replicas of packets can be sent any time in a frame. An enhanced CRA was proposed in [19] to combine symbols from different packet replica(s) other than relying on a decodable replica by utilizing soft-value of individual replicas for decoding. However, both of CRA and ECRA are still not asynchronous protocols, which require frame level synchronization and are not suitable in emerging scenario with heterogeneous and/or varying propagation delay.

Unlike protocols discussed above, Spread Spectrum ALOHA (SSA) is another technology that can be used to improve media access efficiency. Similar to the CDMA system in cellular networks, SSA resolves packet collisions by taking advantage of spread-spectrum code. However, it is vulnerable to the receiving power unbalance, similar to the near-far problem in cellular CDMA systems. To address such a problem, combinations of SSA and IIC, the enhanced SSA (E-SSA), were proposed in [27]–[29], which benefits from unbalanced receiving power, on the contrary.

Note that, there are also reservation based medium access protocols, which may be adopted for the emerging networks with long, heterogeneous, and/or varying propagation delay. For example, satellite networks standards include Demand Assignment Multiple Access (DAMA) [30]. Reservation based MAC protocols show good performance in cases where medium to large volume of data has to be transmitted or for traffic sources which show a periodic (predictable) behaviour, or a high duty cycle where the advantage of Predictive Capacity Estimation (PCE) is apparent. However, the response time of this kind of protocols can be too long for the transmission of short bursts, such as in the internet or in Air Traffic Management (ATM).

III. SYSTEM MODEL

In this paper, to study the emerging wireless networks with long, heterogeneous, and/or varying propagation delay, we consider a scenario with one central destination receiver and multiple (N) transmitters. The propagation delay between a transmitter and the receiver depends on the distances between the transmitter and the receiver. At the transmitters, the total traffic load follows Poisson distribution with parameter λ. For the traffic load, we consider two patterns: 1) the length of the arrival packet is fixed , and 2) the arrival packet's length is variable. With fixed packet length, λ is measured by the number of packet arriving during one packet transmission duration, T, which depends on the packet length and the modulation and coding scheme (a packet transmission duration = $\frac{\text{packet length}}{r \log_2 M}$, where r is the coding rate and M is the modulation index.). For example, the packet transmission duration for a packet of 100 bits with Quadrature Phase-shift keying (QPSK) modulation is 50 symbols (100 *bits*/2 *bits/symbol*). For variable packet length, we measure λ by the number of bits arriving during a symbol time (*bits/symbol*).

All nodes are half-duplex such that a node is unable to receive any packet when it is transmitting, and there is only one common data channel. In the literature, there are random access MAC protocols utilizing orthogonal channels (using frequency-division, code-division or space-division) [31] to support concurrent multi-packet reception, *e.g.*, Multi-Frequency Time Division Multiple Access (MF-TDMA) system. In this paper, we focus attention on the RA scheme supporting packet reception with only one data channel. AFDA can be easily incorporated in these protocols by reserving a number of channels for AFDA usage in a semi-static fashion.

To ensure the integrity and correctness of data packets, the acknowledgement mechanism is widely used. Whenever a packet arrives at the receiver successfully, an ACK-message will be sent to the source node to inform a successful transmission. However, using co-channel ACK messages may not always be preferable. Studies in [24] showed that the ACK messages may degrade the throughput for RA schemes if the propagation delay is significant. Considering the impact of propagation delay, new acknowledgement and retransmission mechanisms are needed, which is out of the scope of this paper. For simplicity, it is assumed that packets are transmitted without the co-channel ACK message.[1]

For packet decoding at the receiver, it is assumed that channel information is always available, which can be acquired by channel estimation and tracking techniques proposed in [9].

In the following, we propose AFDA, a new MAC protocol utilizing diversity transmission and exploiting interference cancellation. Comparing to existing schemes, the salient merits of AFDA include

1) No network wide synchronization requirement. AFDA can be implemented in an asynchronous way without requiring network wide synchronization at either slot nor frame level.
2) Lower overhead. In CRDSA and other DSA based protocols, random intervals are used between replicas of the same packet. Thus, it is necessary to encapsulate time stamps for the selected slots in each replica of a packet, which increases the overhead. On the contrary, no extra information is needed in AFDA as the replicas are transmitted back-to-back.
3) High throughput and low packet loss ratio (PLR). As an asynchronous MAC protocol, AFDA can achieve higher throughput and lower PLR than SA and DSA.
4) Lower delay. In CRDSA and other schemes using frame structure, the transmission delay for a packet is consisted of several parts, *i.e.*, the waiting time for the next available frame, the waiting time before the first replica is sent out in the available frame, the transmission time and the waiting time between replicas. Comparing to them, AFDA sends packets without holding them in the buffer or waiting for available frame.
5) Lower memory size requirement. To exploit interference cancellation, CRDSA, CRDSA++, CRA, ECRA, and MuSCA all have the receiver to store the raw samples of received signals in a frame all packets received in a frame to start the collision resolution process. Since a long frame is typically required to achieve desired performance, the requirement on the memory size is also high. In AFDA, a sliding window is used to assist in resolving collisions, which is much shorter than a frame and requires much smaller memory size.

IV. ASYNCHRONOUS FLIPPED DIVERSITY ALOHA (AFDA) PROTOCOL

As stated in Sec. I, AFDA is designed for systems with long, heterogeneous, and/or varying propagation delay. To combat the negative impact of the propagation delay, two key techniques, flipped diversity transmission and the Zigzag decoding [9], are employed. In this section, we first introduce the techniques that AFDA uses for collision resolution, *i.e.*, Zigzag decoding [9] and flipped diversity transmission, and explain our motivation to combine it with the diversity transmission. Then, we present the full design of AFDA.

A. COLLISION RESOLUTION IN AFDA

In the following, we explain our motivation to use Zigzag decoding other than interference cancellation in [11]–[16], and how to efficiently combine Zigzag decoding and diversity transmission by a simple flipping operation.

[1] Note that, for applications with strict requirement on reliable packet delivery, out-of-band ACK message using control channel and not interfering the packet transmission can be used.

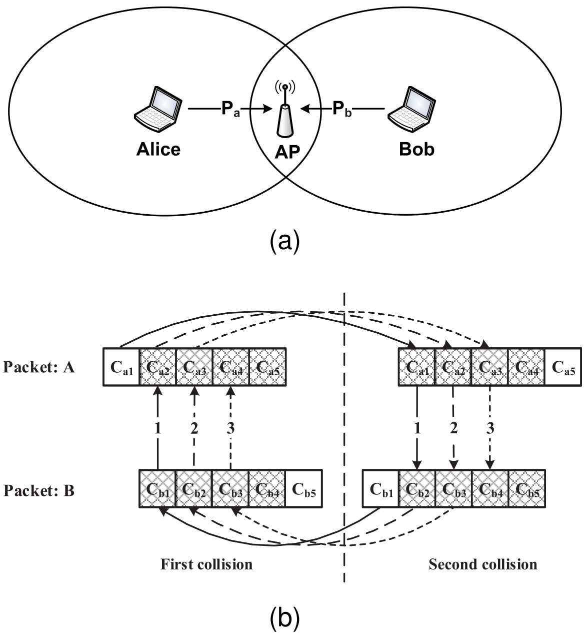


FIGURE 1. Zigzag decoding for hidden terminal problem [9] (The shadowed chunks in Fig. 1b represent the overlapped parts of packets.) (a) Hidden terminal problem. (b) Zigzag decoding.

1) ZIGZAG DECODING

The Zigzag decoding scheme was proposed in [9] to solve the hidden terminal problem in IEEE 802.11 wireless local area networks (WLANs). As shown in Fig. 1a, two nodes Alice and Bob are hidden from each other as they cannot sense the transmissions of the other node. When they transmit simultaneously to the AP, collision happens and the shadowing indicates the packets' overlapping in the collision. According to the DCF used in IEEE 802.11 WLANs, both of them will retransmit. Although each node has to wait for a random backoff interval, collision of retransmitted packets still happens with a high probability as the backoff delay is typically much smaller than the transmission time of a packet. Repeated collisions of the same two packets lead to a severe degradation of the system performance and the waste of radio resources.

To solve this problem, the Zigzag decoding technique uses the random backoff delay of retransmissions to decode collided packets by interference cancellation. For example, as shown in Fig. 1b, the clear chunk C_{a1} of packet A in the first collision and C_{b1} of packet B in the second collision are decoded at first. Then chunk C_{a2} can be decoded by subtracting chunk C_{b1} from the first collision, so as chunk C_{b2}. Both of chunks C_{a2} and C_{b2} are subtracted in the overlapped packets and help decode chunks C_{b3} and C_{a3}, respectively. Thus, the decoding process is proceeded in an iterative way to obtain C_{a4} and C_{b4}, which finally recovers both of packet A and packet B from the collisions.

Compared with the interference cancellation, which is exploited in [11]–[16], and [18], Zigzag decoding can be bootstrapped by only a small clear chunk. In addition, instead of relying on synchronized time slot, Zigzag decoding actually benefits from the asynchronous arrivals of packets. With the features of chunk-bootstrap and asynchronous-decoding, Zigzag decoding can use information provided in multiple packet replicas even when they both collide with other packets, which makes Zigzag decoding an ideal companion to diversity transmission. While diversity transmission can provide extra information needed by transmitting each packet twice or more times, Zigzag decoding provides the way to efficiently utilize these information to finally resolve collisions. In a scenario with long and varying propagation delay, the combination of diversity transmission and Zigzag decoding becomes a promising solution to resolve collisions and enhance system performance.

2) FLIPPED DIVERSITY TRANSMISSION

In the existing diversity transmission schemes, random intervals are used between two replicas of the same packet; otherwise, the two collided packets will collide again after the same delayed period. When these diversity transmission schemes are combined with Zigzag decoding for the system we consider, new problems occur. First, given the long and varying propagation delay, different replicas of the same packet may collide with different packets. Additional overhead has to be added to each packet because the receiver needs to identify the replicas of same packets, so that clear chunks in a replica can be used to decode chunks collided with others. Second, given the two replicas with random interval, it requires complicated channel estimation to guarantee the accuracy of Zigzag decoding. Because the channel condition can be different during the transmissions of different replicas of the same packet, the Zigzag decoding may make a wrong decision if the channel condition for any replica of the same chunk is inaccurate.

To deal with these two problems in the combination of diversity transmission and Zigzag decoding, we design the new flipped diversity transmission scheme. Different from the previous approaches, instead of transmitting two independent replicas separated by a random number of slot, a super packet consisting of the original packet and its flipped replica back-to-back is transmitted. The structure of a super packet is shown in Fig. 2a, where S and E denote the beginning and end of the original packets, respectively.[2] Without any interval between two replicas of the original packet, no overhead will be added and Zigzag can work properly if channel estimation for either replica of the same chunk is accurate as the channel condition for the two replicas are highly correlated.

[2] Note that the link layer typically detects the end of a packet/frame by identifying a flag character at the tail. When a packet is transmitted with its replica back-to-back, the conventional way will fail. One solution is to jointly use the packet length and the flag character, which are already provided in the packet/frame header and tail, respectively. When a super packet is received without collision, the link layer can detect the flag character at the end of the original packet and stop the receiving the replica; when a collision happens, the link layer of the receiver can determine the end of a packet/frame by estimating the super packet's length, which is twice of the packet length.

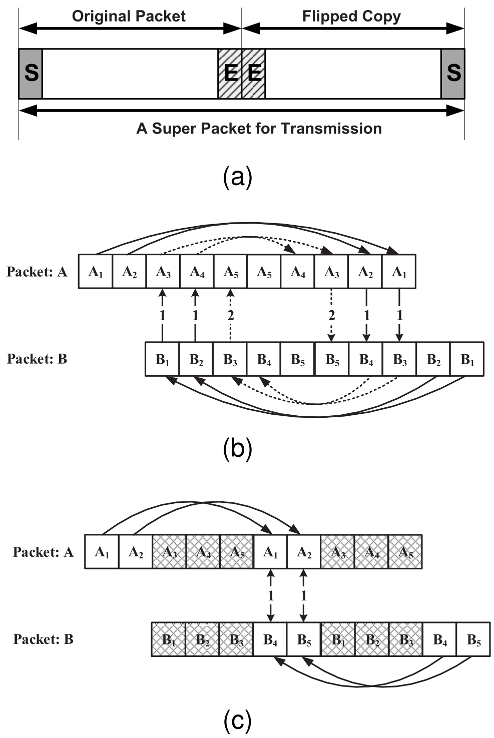


FIGURE 2. Collision Resolution in AFDA (The shadowed chunks in Fig. 2c represent the overlapped parts of packets, which cannot be decoded.) (a) super packet. (b) Zigzag decoding in AFDA. (c) Failed decoding without packet flipping.

An example of decoding two collided super packets is provided in Fig. 2b. A_i and B_i denote chunks of packet A and B, respectively. With clear chunks A_1, A_2, B_1, and B_2, Zigzag decoding can be used to decode chunks B_3, B_4, A_3, and A_4. Then, chunks A_5 and B_5 can be decoded by subtracting B_3 and A_3 from the collision, respectively. The combination of flipped diversity transmission and Zigzag decoding guarantee that any collision among two packets can be successfully resolved. In Fig. 2c, an example is given to show that Zigzag decoding fails to resolve the collision if a packet is transmitted with its replica back-to-back but without flipping its replica. As it is shown, the iterative decoding process stops after the first round decoding because the decoded chunks of packet A (A_1 and A_2) are all overlapped with packet B's chunks (B_4 and B_5), which are already decoded.

B. DESIGN OF AFDA

With the collision resolution techniques above, we design AFDA, a truly asynchronous MAC protocol. In AFDA, no global slot or frame boundary is defined in reference to the timeline at the centralized receiver. Thus, AFDA is more similar to ALOHA, comparing with schemes proposed in [10]–[19].

1) AFDA TRANSMITTER

The transmitter's operations can be summarized as follows:

1) An information packet is first coded using FEC with coding rate as r, and then the transmitter generates a super packet by concatenating the coded packet and its replica as shown in Fig. 2a.
2) At the transmitter side, there is no slot defined globally or locally. At the moment when the packet becomes the buffer head, a super packet is transmitted.

Note that, in CRA [18] and ECRA [19], a synchronous frame structure is required that all transmitters randomly select the slot within a frame simultaneously. Thus, an arrival packet has to store in a transmitter buffer before the next available frame. Besides, when a packet becomes the head-of-line one at the beginning of a frame, its replicas still have to wait for random intervals to be sent. Comparing with that, AFDA is a truly asynchronous protocols and can transmit packets when they arrive without any delay. In addition, CRDSA [11] adopts both the frame and slot synchronization and the duration of a slot is fixed that whenever the incoming information packet or the coded packet is oversize, the packet has to be segmented, which requires larger buffer for the unsent segments, introduces more overhead, and causes longer packet delay. In contrast, AFDA can transmit packets of different sizes without segmentation, which is more favourable for burst packets with various sizes and adaptive coding rates.

2) AFDA RECEIVER

As packets are sent asynchronously, AFDA adopts a sliding window for the receiver to handle the packet decoding and collision resolution. Let the T_s and T_e be the starting and the end of current slide window.

1) The received signal at t is sampled and stored in a memory ($T_s < t \leq T_e$), which can store all samples received within the sliding window.
2) The receiver tries to decode the received packets using the collision resolution technique proposed in Sec. IV-A in an iterative way. For each round, the receiver first tries to decode each sample arrives within the sliding window. Each successfully decoded sample represents a trunk of a packet. As each packet is sent with its replica back-to-back, a decoded trunk of a packet is used to regenerate its replica trunk and to cancel the interference in the remaining samples. The decoding process is terminated when no more sample can be decoded in a round.
3) If $t = T_e$, the sliding window shifts by ΔM. Thus, the new sliding window is for packets arriving between $T_s + \Delta M$ and $T_e + \Delta M$. The remaining samples in the memory, which are received during the first ΔM slots, are dropped.

V. PERFORMANCE ANALYSIS

In this section, we study the performance of AFDA in terms of throughput and packet loss ratio. As it is very difficult if not impossible to obtain the necessary and sufficient condition on when the collisions are resolvable, we derive a performance lower bound of AFDA considering the cases that the packet length is fixed and the collisions are always resolvable. In the

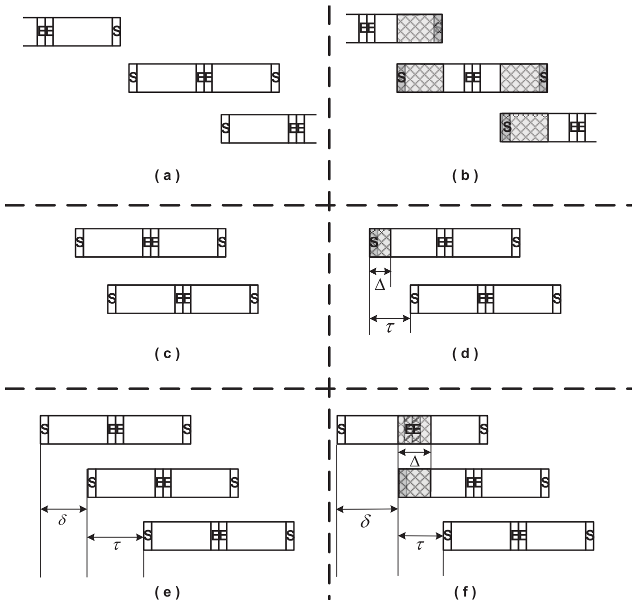


FIGURE 3. Flipped Zigzag decoding cases studies (The shadowed chunks represent the overlapped parts of packets.)

next section, simulation results are used to evaluate the tightness of the bound.

A. RESOLVABLE COLLISION CASES

The following Six cases of resolvable collisions have been identified as shown in Fig. 3, in which the shadowed parts are the blocked chunks collided with other packets, $\Delta \in (0, 2T]$ denotes the transmission duration for the blocked chunks, and δ and τ denotes the inter-arrival time of two colliding packets at the receiver.

1) (a) A packet can be successfully received if either the original or its flipped replica in the super packet has not been collided.
2) (b) When a super packet overlaps both super packets prior and next to it, it could be decoded if either neighboring packet has been decoded successfully.
3) (c) When a collision happens between two packets with interval τ ($\tau < T$, otherwise it is already included in case-a), the two packets are always resolvable.
4) (d) When two packets collide and part of one packet is blocked by a third one, such a collision could be resolved if $\Delta + k\tau < T (k = 1, 2, \ldots), T/(k+1) < \tau < T/k$, and $\Delta < \tau$.
5) (e) When three packets collide, all of them could be decoded if $\delta, \tau \in (T/2, T)$ and $\delta \neq \tau$.
6) (f) When three packets collide, all of them could be decoded if conditions in (d) are satisfied.

It is easy to see that cases (a) and (b) are valid. Because proofs of case (c)-(f) are similar to each other, we prove case (c) at the end of this section and omit others due to the space limitation.

The probabilities that these six cases occur, P_i $(i = 1, 2, \ldots, 6)$, can be derived as follows:

$$P_1 = {P_c}^2 + 2P_c \cdot (e^{-\lambda T} - e^{-2\lambda T}), \quad (1)$$
$$P_2 = 2(e^{-\lambda T} - e^{-2\lambda T})P_r - {P_r}^2, \quad (2)$$
$$P_3 = (1 - e^{-\lambda T})^2 \cdot {P_c}^2, \quad (3)$$
$$P_4 = \Big\{ \lim_{K\to\infty} \sum_{k=1}^{K} \Big[\frac{e^{-\lambda T}}{1+k}(e^{-\lambda T} - e^{-\lambda T \frac{k+1}{k}})\Big] - e^{-2\lambda T}(e^{-\lambda T \frac{1}{k+1}} - e^{-\lambda T})\Big\} \cdot P_c, \quad (4)$$
$$P_5 = (e^{-\lambda T/2} - e^{-2\lambda T})^2 \cdot {P_c}^2, \quad (5)$$
$$P_6 = \Big\{ \lim_{K\to\infty} \sum_{k=2}^{K} \Big[\frac{2e^{-\lambda T/2}}{2+k}(e^{-\lambda T \frac{2+k}{2k+2}} - e^{-\lambda T \frac{2+k}{2k}})\Big] - e^{-\lambda T}(e^{-\lambda T \frac{1}{k+1}} - e^{-\lambda T \frac{1}{k}})\Big\} \cdot {P_c}^2. \quad (6)$$

where P_r is the probability that a packet can be decoded although part of it is blocked by others, and P_c is the probability that a packet does not overlap with any packet. P_r and P_c are given by

$$P_r = P_c \cdot \sum_{k=1}^{\infty} (P_4/P_c + e^{-\lambda T} - e^{-2\lambda T})^k, \quad (7)$$
$$P_c = e^{-2\lambda T}. \quad (8)$$

Note that there exist other more complicated cases (also with less probability to occur) that the collisions are resolvable. Thus, by considering the above six cases only, we can derive the lower bound of the AFDA throughput and the upper bound of the AFDA packet loss ratio (PLR).

B. PERFORMANCE BOUNDS OF AFDA

Considering the resolvable collision cases listed above, the corresponding throughput and PLR of AFDA can be derived. While cases (c), (d), (e), and (f) are resolvable, the two or three packets involved in which could be taken as a collision unit. Such a unit would be resolved if no other packet collides with them (as in cases (c), (d), (e), and (f)), or packets collide with them could be decoded firstly (similar to the middle packet in (a) and (b)). As a result, the probability (P_s) for a packet to be decoded can be obtained by adding probabilities of all identified resolvable cases.

The throughput lower bound S_L and the PLR upper bound PLR_U are given by

$$S_L = \lambda \cdot P_s, \quad (9)$$
$$PLR_U = 1 - P_s. \quad (10)$$

where,

$$P_s = P_1 + P_2 + P_u \cdot \Big(1 + \frac{P_r}{P_c}\Big)^2 + \binom{2}{1} P_4 \cdot \Big(1 + \frac{P_r}{P_c}\Big), \quad (11)$$
$$P_u = \Big[\binom{2}{1}P_3 + \binom{3}{1}P_5 + \binom{3}{1}P_6\Big]. \quad (12)$$

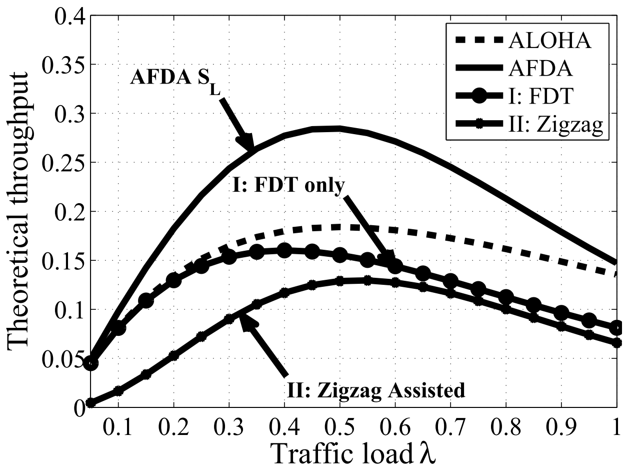


FIGURE 4. Throughput, theoretical results.

C. PROOF FOR CASE (C)

Let PK_A and PK_B denote the two packets arriving at the receiver sequentially with interval τ. Assuming PK_A arrives at time instant 0, then PK_B will arrive at time instant τ. Let $I(\alpha, \beta), I \in \{A, B\}$ denote a chunk lasts from α to β ($\alpha, \beta \in (0, 2T + \tau)$). The decoding process will end when either replica of either packet is decoded.

Using the Flipped Diversity Transmission and Zigzag decoding, chunk $A(\alpha, \beta)$ and its flipped replica $A(2T - \beta, 2T - \alpha)$ contain the same information, so as chunk $B(\alpha, \beta)$ and $B(2(T + \tau) - \beta, 2(T + \tau) - \alpha)$. When chunk $A(\alpha, \beta)$ is known, $B(\alpha, \beta)$ can be decoded by deducting $A(\alpha, \beta)$ from collision parts. Starting from the *clean* chunks $A(0, \tau)$ and $B(2T, 2T + \tau)$, chunks $A(0, k\tau)$, $B(\tau, (k + 1)\tau)$ ($k = 1, 2, \ldots$ $k\tau \leq T$) and their flipped replicas can be decoded. As k increases to K, it can be found that $K\tau < T < (K+1)\tau$. Thus the unknown chunks $A(0, T)$ can be decoded by deducting $B(\tau, (K + 1)\tau)$. Finally, both PK_A and PK_B are successfully decoded.

VI. PERFORMANCE EVALUATION

Extensive simulations have been conducted to evaluate the performance of AFDA. In the physical layer, QPSK modulation is used (2 *bits/symbol*) and the energy per symbol to noise Power Spectral Density ratio E_s/N_0 is 10 dB. No power unbalance has been considered in this work, which is left as a further research issue. The simulation topology is the same as that in the system model in Sec. III, *i.e.*, multiple transmitters send packets to one receiver. In the following, without special illustration, it is assumed that there are infinite number of transmitters generating Poisson traffic with fixed information packet length of 100 bits.

A. CONTENTION RESOLUTION CAPABILITY OF AFDA

We first study the performance of contention resolution capability of AFDA by illustrating the performance gain of the flipped diversity transmission (FDT) and that of the Zigzag decoding. In Fig. 4, the throughput of AFDA is split into two parts and shown separately as curves I and II according to the analysis in Sec. V. Curve-I represents the throughput achieved when at least one of a packet's replicas is received without collision (no Zigzag decoding is needed), and Curve-II is the throughput gain when Zigzag decoding is combined with the flipped diversity transmission. The sum of curve I and II represents the lower bound of the throughput of AFDA. Using ALOHA as a benchmark, it is found that FDT sacrifices part of throughput when the traffic load is high as each packet needs to be transmitted twice. However, as FDT provides diversity in the transmission, the combination of FDT with Zigzag decoding effectively boosts the maximum throughput of AFDA to be almost twice of that with ALOHA.

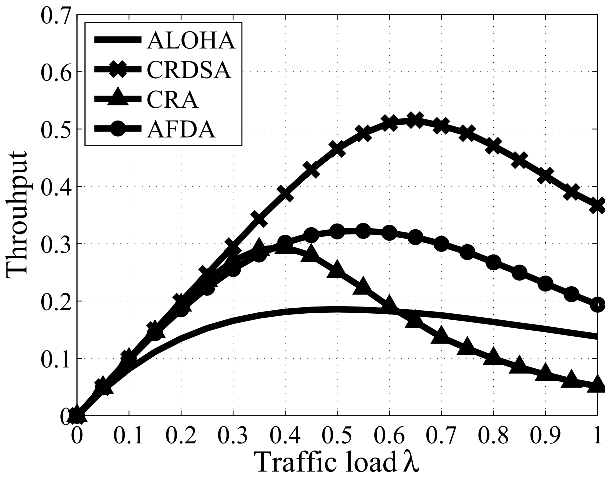
Note that one limitation of the zigzag decoding is that it requires to transmit a packet more than once. For AFDA, which uses the zigzag decoding technique, it can still be advanced in the energy efficiency comparing with Aloha. For Aloha, even if it transmits each packet twice, its throughput will still be lower than that of AFDA. This is because the increased traffic load cause more collisions, which are unrecoverable. In Section VI of [1], FDA (the predecessor of AFDA) was compared with Diversity Slotted Aloha (DSA), which is an extension of Aloha and sends each packet twice. The results demonstrated the advantage of AFDA in the energy efficiency. The issue is that a fair comparison for energy efficiency is to measure the average energy consumption per successful transmission, which is equivalent to the traffic load over throughput. With Aloha, when the traffic load exceeds 0.5 packet/slot, even if each packet is transmitted multiple times, the throughput will not increase, so the spectrum efficiency and energy efficiency both drop quickly. Similar conclusion applies for other MAC protocols, each of which associates with an optimal arrival rate. Different from the PHY layer, once the traffic arrival rate exceeds the optimal value, there is no spectrum-energy tradeoff in the MAC design. Thus, we mainly focus on maximizing the throughput and leave energy efficiency for future research.

B. THROUGHPUT AND PACKET LOSS RATIO

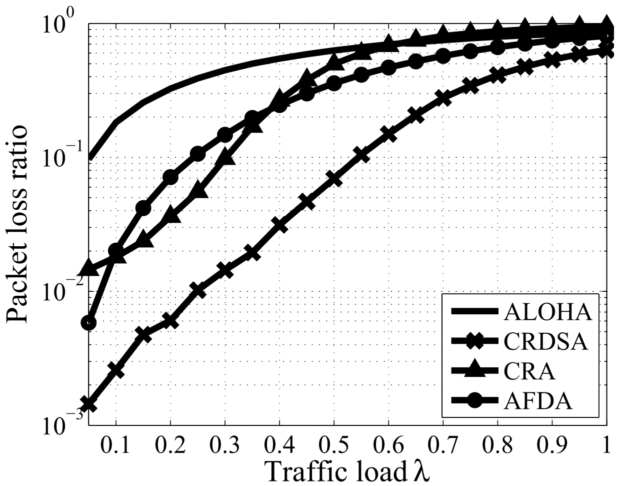
In Figs. 5a and 5b, we compare the performance of AFDA with ALOHA, CRDSA, and CRA in terms of throughput and packet loss ratio (PLR).[3] In the simulation, a slot is set to be as long as the transmission duration of a packet, *i.e.*, 50 symbols (100 *bits* / 2 *bits/symbol*) and the frame size for CRDSA and CRA and the sliding window for AFDA receiver are 100 slots.

As shown in Fig. 5a, the maximum throughput gain of AFDA over ALOHA is about 75% and the PLR is 1 order lower than ALOHA. Note that, the simulated throughput in Fig. 5a is slightly higher than that analytically derived one

[3]For CRDSA and CRA, we only consider two replicas for each packets. The performance of CRDSA and CRA with more than two replicas per packet have been studied in [11] and [18].

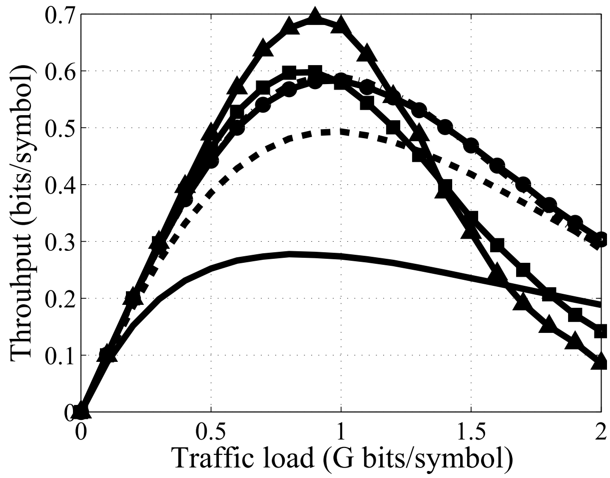


(a)

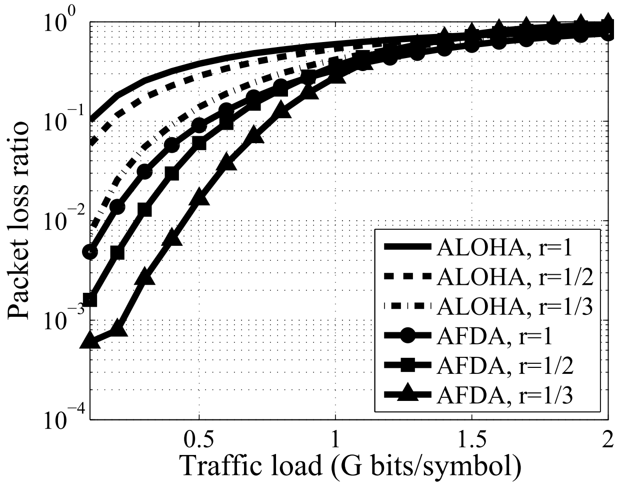


(b)

FIGURE 5. AFDA performance with fixed packet length, simulation results. (a) Throughputs. (b) Packet loss ratios.



(a)



(b)

FIGURE 6. AFDA performance with variable packet length, simulation results (The legends in the two sub-figures are the same. To avoid the overlap between the curves and their legends, legends are only marked in sub-figure b.) (a) Throughputs. (b) Packet loss ratios.

in Fig. 4. However, they are very tight when the traffic load is light. As traffic load increases, FDT with Zigzag decoding can resolve more complicated collisions than the cases we identified in Sec. V, thus its performance is better than the derived bounds.

Comparing AFDA, CRA and CRDSA, it can be observed that CRDSA achieves the highest throughput among the four schemes; AFDA outperforms CRA when the traffic load is higher than 0.4 and keeps close to CRA when the traffic is light. Note that, both CRDSA and CRA rely on time synchronization. Moreover, with random delay between the two replicas of a packet, as stated in Sec. II, additional overheads are needed to identify whether the two are replicas of the same packet, and channel estimation will be more difficult. In addition, the receiver needs a larger buffer to store the colliding packets hoping some future arriving packets can help to decode them, which will further result in a longer delay and more difficulties in implementation.

C. IMPACT OF VARIABLE PACKET LENGTH

Without requiring time synchronization, one advantage of AFDA is that it can also be used in scenarios with variable packet length. In Figs. 6a and 6b, the impact of non-fixed packet length on the throughput and packet loss ratio of AFDA is studied assuming that the information packet length follows exponential distribution with the mean length of 100 bits. In the simulation, FEC with the coding rate $r = 1/2$ and $1/3$ are also considered. For the packet decoding, the Shannon bound capacity is used. Thus, $r \log_2 M = \log(1 + SINR)$ and the decoding threshold is approximated by $\text{SINR}_{th,dB} = 10 \log_2(2^r M - 1)$. In addition, as the packet length is variable, the traffic load and throughput are measured in *bits/symbol*. For the total arrival information bits, G *bits/symbol* is equivalent to $\lambda = G/\log_2 M$ *packets/slot*.

As shown in the figures, AFDA achieves a maximum throughput as 0.58 *bits/symbol* in the simulation, which is 200% of the ALOHA throughput and close to that of AFDA

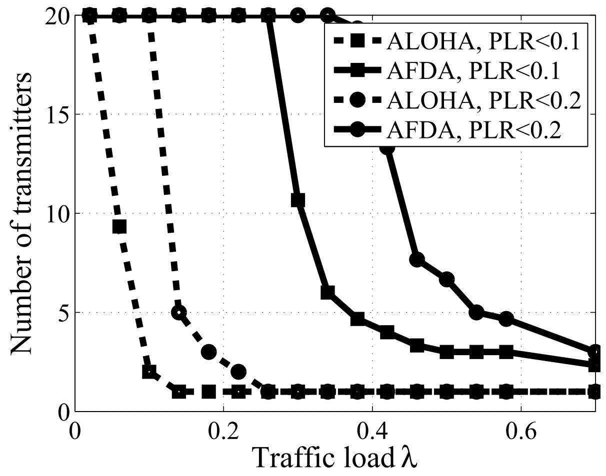


FIGURE 7. Maximum admissible number of transmitters, simulation results.

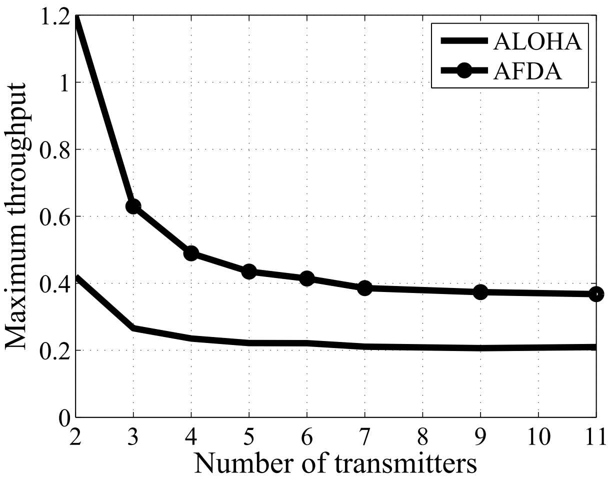


FIGURE 8. Maximum achievable throughputs, simulation results.

with same packet length. When FEC coding is combined with AFDA, it is observed that FEC coding can help increase the throughput and reduce the packet loss ratio when the traffic is medium. For example, with $r = 1/3$ FEC coding, the throughput is increased by 16% and the packet loss ratio is reduced to be below 10^{-3} for light traffic load. However, the performance of AFDA with FEC coding degrades more quickly than that without FEC coding when the traffic load is heavy. This is because the enlarged packet length eventually increases the collision probability.

D. PERFORMANCE WITH FINITE NUMBER OF TRANSMITTERS

In Figs. 7 and 8, we further study the performance of AFDA with finite number of transmitters in terms of admission region and maximum achievable throughput under PLR thresholds of 10^{-1} and 2×10^{-1}. Comparing with infinite transmitter scenario, the random access performance with finite number of transmitters is likely to be better because packet arrivals at the receivers become sparser. When there are N transmitters, the probability for one replica of a packet to be collided is $e^{-2\lambda T\cdot(1-1/N)}$. The fewer the number of transmitters, the lower the collision probability is. As shown in Fig. 7, AFDA effectively enlarges the network admission region by allowing a larger number of transmitters. For instance, given the PLR threshold of 10^{-1} and the aggregated traffic arrival rate of 0.3 packet/slot, the network accommodates more than 10 transmitters using AFDA, while it can only accept 1 transmitter if using ALOHA.

Moreover, it is found that AFDA can achieve a higher maximum throughput with the same number of transmitter(s) than ALOHA. Fig. 8 shows the maximum throughput that achieved by optimizing the traffic load of each transmitter. It is observed that the maximum throughput for a network with 20 transmitters using AFDA is 100% higher than that using ALOHA. Besides, the improvement is even more significant when the number of transmitters is less than 20. Note that when we set the traffic load to maximize the throughput, the PLR using AFDA is lower than that using ALOHA.

VII. CONCLUSION

In this paper, for networks with long, heterogeneous, and/or varying propagation delay, we have proposed the AFDA protocol, in which a new flipped diversity transmission scheme has been proposed to allow the receiver using Zigzag decoding to effectively decode colliding packets. Performance of AFDA has been studied and simulation results show the effectiveness of AFDA in networks with long, heterogeneous, and/or varying propagation delay, and its performance gains in terms of throughput, packet loss ratio, and admission region.

There are some further research issues to fully understand the performance of AFDA and improve its efficiency. In this paper, we assume perfect channel estimation. For practical implementation, it might be challenging for the decoder to identify that there exist such a packet, whose both headers are collided with others, in the collision. Another practical issue for proposed AFDA is computational complexity. How to consider MAC design for multihop, multipath networks will be a more challenging, and important issue [32], [33].

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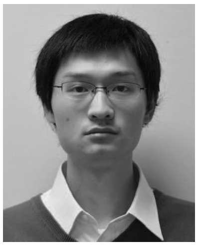

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