Hybrid Collision Avoidance-Tree Resolution for M2M Random Access

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Wireless machine-to-machine (M2M) communication with synchronized traffic patterns plays an important role in many aircraft systems. Recent research has separately examined collision avoidance mechanisms, such as presmoothing and access barring, as well as collision resolution mechanisms, such as tree resolution, for M2M random access. In contrast, we examine the combination of collision avoidance and tree collision resolution into hybrid M2M random access protocols in the context of the popular Long-Term Evolution wireless system.

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I. INTRODUCTION

A. Motivation

Machine to Machine (M2M) communication is an emerging type of communication of numerous devices, such as hundreds of sensors, with a central control unit [1]–[4]. M2M communication is typically either nonsynchronous, i.e., not correlated with a particular event, or synchronous, i.e., correlated with an event, such as system start-up or resynchronization of all sensors. Synchronous M2M traffic is particularly challenging for communication systems due to the bursty traffic pattern.

Sensors are critical for a wide range of functions on board of aircraft. At the same time, weight reduction is important for aircraft [5]. Therefore, wireless communication has attracted significant attention for aircraft applications [6]. Although wireless communication for avionics poses significant challenges [7], [8], extensive efforts are under way to make wireless communication feasible on board [9]. For instance, in September 2015, a new frequency band has been allocated for wireless avionics intracommunications (WAIC) [10], i.e., wireless communications between two or more points on a given aircraft. Recent research has examined distributed detection in aircraft [11], [12] as well as advanced wireless ultrawide band communication for safety-critical avionics [13]–[15]. Studies have also sought to understand the noise effects due to wireless random access channel (RACH) communication [16] and to characterize the in-cabin wireless channel [17].

With the advances in wireless sensor technology and their widespread deployment on aircraft, it will be important to develop effective communication protocols for synchronous M2M traffic in WAIC settings. However, while medium access control (MAC) is generally recognized as an important component of aeronautic systems [18], [19], there is scant prior MAC research for M2M traffic in WAIC settings, where the total maximum number of communicating machines is known. To the best of our knowledge, only Leipold *et al.* [20] examined synchronous M2M traffic in the context of in-cabin wireless communication. However, only for a limited number of up to 40 communicating machines. For common sensor applications, such as sensors for cabin pressure, fuel tank sensors, fuel line sensors, and proximity sensors, very high numbers of sensors, i.e., communicating machines, on the order of hundreds or thousands of communicating machines are anticipated [21].

B. Contributions of This Study

This study introduces and evaluates a new class of tree-based random access (TRA) MAC protocols for synchronous M2M traffic. We combine collision avoidance techniques, such as presmoothing and access barring, with tree collision resolution to form the class of hybrid collision avoidance-tree collision resolution random access MAC protocols. Within this class of random access MAC protocols, we define two specific protocols, namely PreBOTRA, which combines presmoothing [prebackoff (PreBO)] with tree-based collision resolution (tree-based random access), and DABTRA, which combines dynamic access barring (DAB) with tree-based collision resolution. These novel protocols are well suited for settings with a known number of communicating machines (devices), such as preconfigured communication systems in an aircraft cabin. We conducted extensive simulations to evaluate the throughput and delay of successful random access requests as well as the request drop probability of PreBOTRA and DABTRA. In comparison with MAC protocols employing either collision avoidance or tree collision resolution, the hybrid PreBOTRA and DABTRA protocols demonstrate favorable performance characteristics.

C. Article Structure

Section II reviews related work on random access strategies for M2M traffic, including strategies based on collision avoidance and strategies based on collision resolution. Section III provides general background on the wireless long-term evolution (LTE) RACH, synchronous M2M traffic, and TRA. Section IV examines collision avoidance mechanisms for M2M traffic, including PreBO smoothing and dynamic access barring. Section V specifies how collision resolution can be achieved for M2M traffic through TRA. Section VI introduces hybrid collision avoidance-tree collision resolution protocols by combining collision avoidance through PreBO or dynamic access barring with tree-based collision resolution. In particular, the PreBOTRA protocol is introduced in Section VI-A, while the DABTRA protocol is presented in Section VI-B. PreBOTRA and DABTRA are extensively compared through simulations with a range of random access benchmarks in Section VII. Section VIII summarizes this study and outlines directions for future research.

II. RELATED WORK

We first briefly review the general area of random access strategies for M2M traffic. We then review in detail the related random access studies with a focus on collision avoidance and a focus on collision resolution with tree-based approaches.

A. General Random Access Strategies for M2M Traffic

Wei *et al.* [22], [23] have analyzed LTE random access for synchronous M2M traffic. In follow-up research, Cheng *et al.* [24] and Wei *et al.* [25] have proposed to estimate traffic arrivals and to dynamically allocate resources for M2M traffic. Cheng *et al.* [26] have examined prioritization to serve M2M traffic according to its delay tolerance. Inaltekin and Wicker [27] have conducted a Nash equilibrium analysis of M2M arrivals with a game-theoretic perspective of selfish users reaching the RACH. Lioumpas and Alexiou [28] investigated the effects of uplink scheduling for mitigating M2M arrivals. They proposed dynamic allocation of different random access resources to better accommodate the variable M2M arrivals. The general strategy of allocating additional random access resources for M2M traffic has been examined from a number of perspectives. A resource control perspective has been considered in [29], while a game theory-based perspective has been investigated in [30]. The perspective of reporting-based resource allocation has been introduced in [31], while delay requirements were considered in [32] and [33] and a context-aware perspective has been considered in [34].

Alternative strategies for the challenging synchronous M2M traffic have been explored in several studies. Data transmission schemes based on examining the signaling for random access have been proposed in [35] and [36]. Grouping-based radio resource management [37]–[39] has been proposed to prioritize different user groups. Learning mechanisms for random access slot selection have been explored in [40]. A code expansion random access strategy has been introduced in [41]. At the network management level, a capillary network gateway has been proposed in [42].

B. Collision Avoidance for M2M Traffic

For one-shot M2M arrivals, Duan *et al.* [43] have examined DAB in an LTE system. Duan *et al.* dynamically modify the LTE access class barring (ACB) parameter according to the collided and successful preamble transmissions. Effectively, DAB strives to modify the arrival rate so as to maintain a uniform arrival rate to the RACH. DAB requires a new parameter transmission to all registered devices in the network at the end of each frame. Ko *et al.* [44] have exploited timing advance information in the random access messages to develop a novel access scheme for fixed location devices. The resolution of the timing advance information requires two contending users to be at least 156 m apart. Wang and Wong [45] merged DAB with the timing advance information approach. The parameters of both techniques were molded into a single optimization problem and the effects of the parameters were investigated under heavy M2M traffic.

Group paging, where a set of distributed user equipment (UE) nodes need to be connected to a central enhanced Node B (eNB), is closely related to synchronous M2M traffic models. Jiang *et al.* [46] introduced a PreBO approach for group paging and analyzed the optimal paging size for a given initial number of M2M devices. However, the suggested technique has a scaling problem due to the LTE backoff mechanism after a collision [47]. The scaling problem is partially solved in [48] by forming different clusters for group paging and treating the cluster heads at a different phase as another group paging process. This solution assumes that the cluster heads are able to carry the data transmitted in their cluster within a single slot as an optimized (aggregate) forwarding operation. This aggregate forwarding operation in turn gives rise to a new scaling problem [48].

Further solutions for M2M overload based on access barring have been examined in a few studies. ACB variations have been investigated in [49], while a full rejection of M2M traffic depending on the traffic load has been investigated in [50]. Fast adaptive slotted ALOHA with access barring was introduced in [51] and arrival estimation for access barring was investigated in [52]. For one-shot arrivals, Lien *et al.* [53] proposed a cooperative access barring scheme for multicellular M2M communications. The multitude of picocells is exploited to offload some M2M communication between cells depending on the arrival density; thus essentially smoothing the M2M traffic load across a spatial region. Wali and Das [54] proposed heterogenous networks as a solution to overload M2M traffic scenarios.

For our hybrid MAC protocols, we build on the reviewed collision avoidance research. We employ DAB [43] as well as presmoothing backoff and combine these collision avoidance techniques with TRA.

C. TRA for M2M Traffic

General stability analyses of tree-based collision resolution for bursty traffic models have been conducted in [55]. For simultaneous batch arrivals from an unknown number of devices, the batch resolution algorithms in [56]–[59] estimate the number of devices and conduct random access for their requests. In contrast, we consider an on-board avionic setting with a known number of devices.

Madueno *et al.* [60] proposed a collision resolution method using a q-ary tree splitting algorithm for synchronous M2M arrivals in LTE. The tree splitting algorithm splits the available preambles into groups. Preamble groups are assigned to the collided requests with a specific backoff timer. Although the tree splitting approach serves all the requests faster compared to previous approaches, it achieves a long run average throughput (of successful request per preamble per slot) of only 0.20. Laya *et al.* [61] and Vázquez-Gallego *et al.* [62] have examined tree-based contention resolution in the context of distributed queueing random access for M2M traffic. Distributed queueing maintains a contention resolution queue for the initial access requests and a data transmission queue for the successful access requests. Adaptations of LTE random access to distributed queueing with tree-based contention resolution have been outlined in [61]. Energy harvesting aspects of TRA for M2M traffic have been examined in [63] and [64].

Our hybrid MAC strategy is to employ a collision avoidance technique prior to TRA so as to enhance the effectiveness of the tree-based collision resolution.

D. Hybrid Random Access

Hybrid random access protocols generally combine multiple random access mechanisms, e.g., an “outer” mechanism that is followed by an “inner” mechanism [65]. Such hybrid inner-outer random access mechanisms are quite common in MAC protocols for a wide variety of systems. For instance, in wireless communication, the standard LTE RACH with access barring employs the access barring mechanism as outer mechanism followed by the slotted Aloha contention with backoff as inner mechanism. Another example is the combination of a partitioning (grouping) procedure as the outer protocol with dynamic frame Aloha [66], [67] for a radio frequency identification MAC protocol [65], [68].

Hybrid random access protocols for M2M traffic in communication systems have received relatively little research attention to date. The few existing approaches are complementary to our combination of collision avoidance and tree-based collision resolution. Specifically, a hybrid random access scheme that shares resources between the RACH and data transmission channel was investigated by Wiriaatmadja and Choi [69]. Wiriaatmadja and Choi modeled human to human traffic and M2M traffic in order to optimally allocate resources for the data channel and the RACH. Liu *et al.* [70] and Verma *et al.* [71] combined conventional carrier sense multiple access for collision resolution with a reservation-based time division multiple access. Hybrid random access combining a contention-based and contention-free access has been examined for M2M in a home setting in [72].

III. BACKGROUND

In this section, we provide background on the main concepts that are the foundations for this study, namely, LTE, M2M traffic, as well as TRA.

A. LTE Random Access Channel

We consider the LTE RACH as context for our study for two main reasons. First, the majority of the present research on accommodating M2M traffic in wireless networks examines protocol mechanisms in the context of the LTE wireless standard [73], which is specified by the 3rd Generation Partnership Project. While the WAIC standard for avionic settings is currently under development, it is likely that the WAIC standard will incorporate aspects from existing standards, such as LTE, that have been extensively researched in recent years for a wide variety of challenging traffic patterns, including M2M traffic. Second, the LTE RACH is based on a variant of slotted Aloha and we abstract the LTE RACH to a slotted Aloha system model for our study. This model can transfer to a wide variety of random access technologies with synchronization. For example, the IEEE 802.15.4 time slotted channel hopping [74] has such synchronization.

The LTE random access involves four message transfers: A UE device that wants to access the network uniformly randomly selects one of the M available preambles in a random access subframe to send its initial request message (MSG) 1 without any identifier. The central eNB cannot differentiate multiple preamble receptions from a single preamble reception due to lack of a user-specific identifier. If the eNB receives any signal on any of the allocated preambles, it responds on the respective preamble, approving the link quality with MSG 2. Lack of a MSG 2 would mean that the preamble could not be received due to some hardware failure or pathloss. When MSG 2 is received by the UE, the UE responds with a connection request MSG 3. MSG 3 contains the identifier of the requesting UE. Thus, if multiple UEs reach the eNB at this point, a collision occurs. If a collision occurs, then MSG 4 is not sent and the UE declares that there was a collision. The UE retries to access the channel after a uniform backoff over the next Γ slots; for simplicity, we use the same backoff duration parameter Γ for the backoff after a collision and for the PreBO specified in Section IV-A. If there was no collision of MSG 3, then the UE receives an access or denial answer MSG 4 depending on the system load. If a UE cannot complete the random access procedure within the prescribed trial limit, then the UE request is dropped. Our study focuses on the random access aspect of the contention of MSG 3 transmissions. For simplicity of exposition, we model the LTE RACH to operate on a slot-by-slot basis, whereby each slot provides M preambles.

B. Machine-to-Machine Traffic

1) Traffic Model: In case of an emergency alarm, resynchronization event, or system start-up in an aircraft, the N devices will try to simultaneously (in synchronism) use the RACH. An elementary M2M traffic model, the so-called Delta model, lets the N UE requests arrive in the same single time slot, i.e., the synchronous arrival period (activation time period) is $T_A = 1$. The model notations are summarized in Table I.

A more sophisticated M2M traffic model can be based on the beta distribution [75]–[77]. The M2M devices mostly sleep and only wake up to communicate specific events, e.g., detection of a fire by a set of heat sensors, resulting in bursts of UE request arrivals. Within a prescribed activation time period T_A, $T_A > 1$, the random activation time t, $[0 \leq t \leq T_A]$, of a given UE device is modeled with the beta distribution

$$\text{beta}(t) = \frac{t^{\alpha-1}(T_A - t)^{\beta-1}}{T_A^{\alpha+\beta-1} B(\alpha, \beta)} \tag{1}$$

where $B(\alpha, \beta)$ denotes the beta function $B(\alpha, \beta) = \int_0^1 t^{\alpha-1}(1-t)^{\beta-1}dt$. Following [78], we set $\alpha = 3$ and $\beta = 4$.

2) Synchronous Arrival Detection: Random access protocols for M2M traffic generally rely on some M2M traffic (synchronous arrival) detection mechanism to switch from regular (nonM2M) operation to the M2M random access operation mode and back to the regular mode when the M2M traffic subsides. For instance, the central LTE eNB can monitor an energy detector that detects a high number of MSG 3 collisions, indicating the onset of M2M traffic [31]. For specific system settings, there may be outside triggers for switching to M2M traffic mode, e.g., alarms in smart meters [79], or specific alarms or system start-up signals in an aircraft cabin.

C. Background on TRA

TRA has been extensively studied for (nonsynchronous) Poisson process arrivals. Capetanakis [80] showed that the stable throughput (of successful requests per slot) of the binary tree algorithm, that uses a dedicated binary tree to resolve the collisions, is 0.34. The optimum (dynamic) tree protocol [80, Section III-A] with an optimal branch size for the first branch, followed by binary tree branchings increases the throughput to 0.4295. Extensions of the optimum tree protocol generally exploited specific feedback information or interference cancellation techniques to achieve further throughput increases. For instance, the modified tree algorithm [81] uses the data of an empty or a collided resource to estimate and resolve a wasted slot before it occurs, achieving a throughput 0.4622. The first come first served-based contention resolution [82] adapts the decision of joining a slot or not and the number of available slots with the resource usage feedback, achieving a throughput of 0.4877. The successive interference canceling tree algorithm extracts data from collided slots to achieve a throughput of 0.693 [83], [84]. We consider the optimum tree protocol [80, Section III-A] in our hybrid collision avoidance-tree resolution protocol development as it is a relatively simple protocol that can be readily employed in LTE wireless systems.

IV. COLLISION AVOIDANCE

In this section, we examine collision avoidance mechanisms for M2M traffic. We consider prebackoff smoothing and conduct a probabilistic analysis of the PreBO dynamics. We then consider DAB as an alternative collision avoidance mechanism.

A. PreBO Smoothing Motivation

Our motivation for PreBO is twofold. First, we aim for a low collision rate by presmoothing the burst of synchronously arriving UE requests. Second, the presmoothing aids in obtaining a good estimate of the arrivals, which in turn aids in effectively adapting the dynamic TRA.

1) Low Collision Rate: Consider a slotted Aloha random access system with N users (UE requests) and M preambles (which are equivalent to channels). In a given slot, each user uniformly selects one of the M preambles for transmission with probability $1/M$. The probability that a given preamble contains one successful transmission is

$$\binom{N}{1}\left(\frac{1}{M}\right)\left(1-\frac{1}{M}\right)^{N-1}. \tag{2}$$

If we control the system such that the number of users N contending for transmission in a slot is equal to the number of preambles M, i.e., $N = M$, the probability of successful transmission becomes

$$\left(1-\frac{1}{M}\right)^{M-1}. \tag{3}$$

Fig. 1 illustrates that the probability of successful transmission on a given preamble in a slot, and thus the throughput of the slotted Aloha access system, increases with decreasing number of preambles M, while controlling the number of users N to match the number of preambles ($N = M$). This increase of the random access throughput is the main motivation for tree-based (splitting) collision resolution random access protocols [85], [86] that split the overall system into small groups. We combine the PreBO

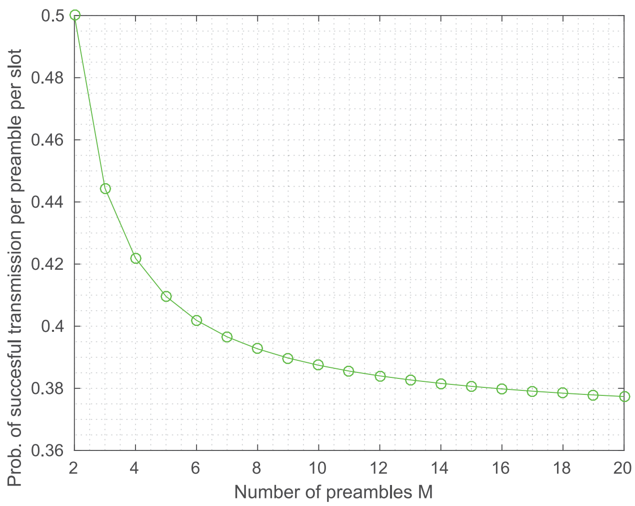

Fig. 1. Probability of successful transmission on a preamble in a slot when the number N of users is controlled to be equal to the number M of preambles.

mechanism with the TRA mechanism (see Section V) to form the PreBOTRA protocol in Section VI-A.

2) Arrival Smoothing as Enabler for Optimal Dynamic Tree-based Collision Resolution: Generally, the high-performance dynamic TRA mechanism [80] requires relatively accurate estimates of the number of requests colliding on a preamble in order to initiate the tree-based collision resolution with the optimal number of tree branches. However, in the LTE system, the number of the collided users on a preamble in a given slot cannot be deduced. The direct estimation of the Beta distributed M2M request arrivals is also very challenging [87]. Moreover, in the LTE RACH, the request arrivals are distributed over M preambles; thus, the estimation of the collided requests on a given preamble is prone to large estimation errors.

Our PreBOTRA strategy bypasses this challenging estimation of the arrivals, which are needed to optimally configure the collision resolution tree, through the PreBO. The PreBO uniformly distributes the requests over Γ backoff time slots with M preambles available in each slot. This uniform distribution shapes the request arrival process to follow approximately a Poisson distribution [88], [89], as illustrated in Section IV-C. For the following reasoning, we consider the Delta traffic model, i.e., all N UE requests arrive in the same slot; we specify the full PreBO protocol with arrivals over multiple slots in Section IV-B.

Capetanakis [80, Section III-A] showed that the optimal number of initial tree branches is proportional to the mean μ of a Poisson distributed number of requests to be processed divided by 1.15; whereby for a large number of requests, the optimal number of initial branches equals $\mu/1.15$. Instead of configuring the number of tree branches, we configure the number of PreBO slots Γ. Importantly, our number of PreBO slots is analogous to the number of initial tree branches in [80]. Based on this key insight, we configure the number of PreBO slots Γ as follows. We first note that with a total of N UE requests and M preambles per slot, there are on average N/M UE requests to be processed on a given preamble (across all PreBO slots). Noting that N/M is a moderately large number in typical M2M scenarios, the optimal number of PreBO slots is

$$\Gamma = \frac{N}{1.15M} \tag{4}$$

which we round up to obtain an integer number of PreBO slots.

The second key insight about the arrival smoothing of PreBO is that the uniform random distribution of the N/M UE requests on a preamble into Γ backoff slots corresponds to executing the initial tree branching of the optimal tree protocol [80, Section III-A]. For the subsequent tree branchings, two branches, i.e., the binary tree is optimal [80, Section III-A].

B. Smoothing PreBO Protocol Specification

The reasoning about the correspondence between our PreBO smoothing and the optimal tree protocol [80, Section III-A] considered N arriving UE requests in a single slot. However, M2M requests my arrive over a time period of multiple T_A slots, see Section III-B. For simplicity, we maintain for the arrivals over multiple slots the same number of

$$\Gamma = \left\lceil \frac{N}{1.15M} \right\rceil \tag{5}$$

PreBO slots. Specifically, the $n,\ n \leq N$, UE requests arriving in a given slot t are uniformly randomly distributed over the next Γ slots. That is, each UE node independently randomly selects a given backoff slot $t+\gamma,\ \gamma = 1, 2, \ldots, \Gamma$, with uniform probability $1/\Gamma$.

C. Smoothing PreBO Analysis

For the analysis in this section, we consider N arrivals in a single slot, i.e., the Delta M2M traffic model; this analysis is compared with simulations for both Delta and Beta arrivals in Section VII. Independently randomly distributing N UEs into Γ backoff slots results in the probability mass function (pmf)

$$P_{B_\gamma}(b) = \binom{N}{b} \frac{1}{\Gamma}^{b} \left(1 - \frac{1}{\Gamma}\right)^{N-b},\ b = 0, 1, \ldots, N \tag{6}$$

for the number B_γ of UEs in a given backoff slot $\gamma,\ \gamma = 1, 2, \ldots, \Gamma$. Fig. 2 illustrates the pmf $P_{B_\gamma}(b)$ for typical M2M communication settings. We observe from Fig. 2 that for the typical large number of requests N (on the order of thousands) relative to the number of preambles M, the pmf $P_{B_\gamma}(b)$ closely approaches the normal distribution with mean $1.15M$ and variance $1.15M/(1 - 1.15M/N) \approx 1.15M$. Moreover, we observe from Fig. 2 that the support of the pmf $P_{B_\gamma}(b)$ can be reasonably approximated to the range $1.15M/2, \ldots, 3 \cdot 1.15M/2 = 27, \ldots, 81$ (for the considered typical number of preambles $M = 54$).

Through conditioning on the number B_γ of UEs in a given backoff slot γ, we obtain the pmf for the number

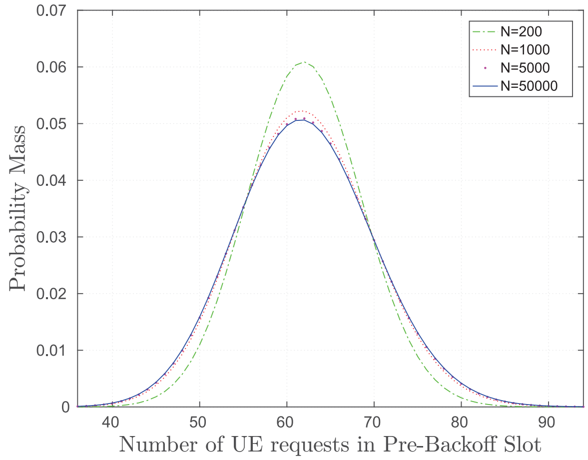

Fig. 2. Probability mass function for number B_γ of UE requests in a given PreBO slot γ out of a total of $\Gamma = \lceil N/(1.15M) \rceil$ PreBO slots for $M = 54$ preambles and different numbers of UE requests N.

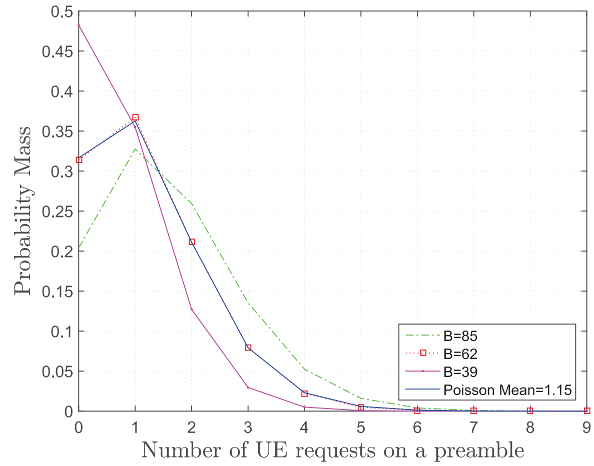

Fig. 3. Probability mass function (pmf) for number $\Pi_{\gamma,\pi}$ of UE requests on a given preamble π within a given PreBO slot γ for different given numbers B_γ of UE requests in a given backoff slot γ. The pmf of $\Pi_{\gamma,\pi}$ approximates the pmf of a Poisson random variable with mean 1.15.

$\Pi_{\gamma,\pi}$ of UEs on a given preamble π, $\pi = 1, 2, \ldots, M$, within a given PreBO slot γ, $\gamma = 1, 2, \ldots, \Gamma$, as

$$P_{\Pi_{\gamma,\pi}}(i) = \sum_{b=i}^{N} P_{B_\gamma}(b) \binom{b}{i} \frac{1}{M}^{i} \left(1 - \frac{1}{M}\right)^{b-i}, \quad i = 0, 1, \ldots, N. \tag{7}$$

Alternatively, PreBO can directly distribute the N UE requests uniformly randomly over the ΓM preambles covered by the Γ backoff slots. Then

$$P_{\Pi_{\gamma,\pi}}(i) = \binom{N}{i} \left(\frac{1}{\Gamma M}\right)^{i} \left(1 - \frac{1}{\Gamma M}\right)^{N-i}, \quad i = 0, 1, \ldots, N. \tag{8}$$

Inserting Γ from (4) gives

$$P_{\Pi_{\gamma,\pi}}(i) = \binom{N}{i} \left(\frac{1.15}{N}\right)^{i} \left(1 - \frac{1.15}{N}\right)^{N-i}, \quad i = 0, 1, \ldots, N. \tag{9}$$

In order to avoid notational clutter, we abbreviate $P_{\Pi_{\gamma,\pi}}(i)$ to P_Π. Notice that the mean of $\Pi_{\gamma,\pi}$ is 1.15. Also, notice that for large M2M systems, i.e., for $N \to \infty$, the binomial distribution in (9) converges by the Poisson limit theorem [90] to the Poisson distribution with parameter 1.15, i.e., to $P_\Pi(i) = e^{-1.15} 1.15^i / i!$.

Fig. 3 illustrates the pmf P_Π for the typical range of numbers B of node requests in a given backoff slot ranging from $B = 27$ to $B = 81$. We observe from Fig. 3 that with probability of roughly one third, there is only one node request on a given preamble, resulting in successful random access. We also observe that if there are multiple node requests on a given preamble, i.e., a collision occurred, then the number of collided requests is typically small, in the range from two to five. A higher number (of six or more) collided requests occurs only rarely.

We note that the correspondence between our PreBO and the optimal tree protocol [80] that we outlined in Section IV-A2 would be exact if the pmf P_Π were a Poisson distribution. However, as illustrated in Fig. 3, the pmf P_Π only approximates a Poisson distribution. Thus, the correspondence between our PreBO and the optimal tree protocol [80] is approximate.

D. Dynamic Access Barring

In access barring, the eNB broadcasts an ACB parameter between zero and one to all UEs. A UE independently draws a random number between zero and one and compares its random number with the ACB parameter. If the UE's number is smaller than the ACB parameter, then the UE waits for a future slot, and then retries until it passes the access barring. If the UE's number is larger than the ACB parameter, then the UE immediately advances to the LTE random access contention.

DAB [43] adjusts the ACB parameter dynamically based on the collision history and the resulting estimate of the number of UE requests that will advance to the random access contention in the upcoming slot. DAB broadcasts the updated ACB parameter to the UEs in each slot.

V. COLLISION RESOLUTION: TRA

A. TRA for M2M Traffic

TRA has been extensively studied for Poisson traffic, see Section III-C. To the best of our knowledge only the prior study [60], reviewed in Section II-C, has employed TRA for M2M traffic. In contrast to the prior studies on TRA, we combine the collision avoidance mechanism from Section IV with TRA to efficiently serve bursty M2M traffic.

More specifically, prior studies on dynamic TRA employed estimation methods with Poisson traffic. The bursty M2M traffic would require novel estimation methods for the dynamic TRA. We bypass this challenging estimation problem by executing a collision avoidance mechanism prior to feeding the UE requests into the TRA. As we demonstrated

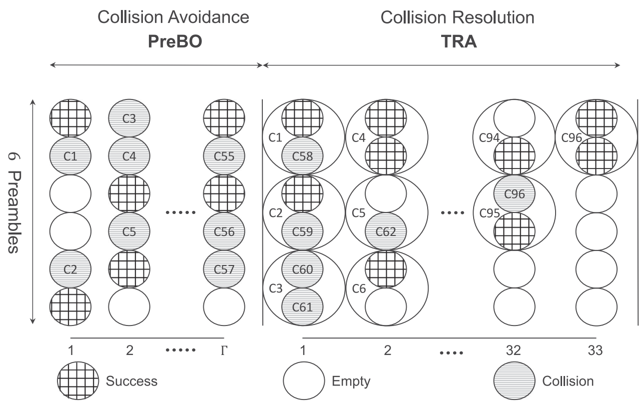

Fig. 4. Example illustration of PreBOTRA operation for $M = 6$ preambles: 57 preambles out of the 6Γ preambles during the PreBO collision avoidance phase have a collision, i.e., were randomly selected by a set of $\Pi_{\gamma,\pi} \geq 2$ UE requests. Collisions are resolved through binary TRA, i.e., each set of collided UE requests is directed to a group of two preambles.

in Section IV-A, the PreBO smoothes the bursty arrivals to approximate a Poisson distribution. Thus, after the PreBO, any of the tree algorithms can be employed to achieve high performance reliable random access in LTE.

B. Specification of TRA Protocol

After the collision avoidance mechanism, the TRA protocol sequentially processes the UE requests on a given preamble. In particular, in case of the PreBO collision avoidance, the $\Pi_{\gamma,\pi}$ UE requests on preamble π in a given PreBO slot γ are processed as follows. If $\Pi_{\gamma,\pi} = 1$, then the single UE request is successful. If $\Pi_{\gamma,\pi} \geq 2$, then we sequentially launch a binary (two branches) TRA (collision resolution) protocol for these UE requests. Specifically, these UE requests are directed to a preamble group consisting of two preambles in an upcoming slot. Note that with M preambles there are $M/2$ preamble groups for binary tree collision resolution in a slot. The process of directing UE requests to a preamble group is repeated until all of the UE requests have been served.

VI. HYBRID COLLISION AVOIDANCE—TREE RESOLUTION PROTOCOLS

A. Pre-Backoff TRA (PreBOTRA)

1) Protocol Specification: The overall PreBOTRA protocol is a concatenation of the PreBO specified in Section IV-B and the TRA specified in Section V-B. The operation of the resulting overall PreBOTRA protocol is illustrated for an example with $M = 6$ preambles in Fig. 4. In the illustrated example, 57 preambles (out of the total of 6Γ preambles available for PreBO) experience a collision, i.e., contain two or more UE requests. Starting with slot $\Gamma + 1$, the binary TRA is launched for each of the 57 collisions. For the binary TRA with the $M = 6$ preambles, there are $M/2 = 3$ preamble groups in each slot during the TRA collision resolution. In the illustrated example, collision 1 from the first PreBO slot results in one success and one collision (C58) in the first TRA slot. Such new collisions are then recursively resolved with TRA. In the illustrated example, a total of $96 - 57 = 39$ new collisions occur during the TRA.

Generally, when synchronous M2M arrivals are detected (see Section III-B2), PreBOTRA initiates the PreBO with Γ [see (5)] slots. UE requests arriving for any slot during the activation time period T_A, $T_A \geq 1$, are distributed by the PreBO over slots T_A, $T_A + 1, \ldots, T_A + \Gamma - 1$, as illustrated for Delta arrivals with $T_A = 1$ in Fig. 4. For simplicity of the protocol, the TRA collision resolution always starts Γ slots after the beginning of the synchronous M2M arrivals, as illustrated in Fig. 4, even when $T_A > 1$. Thus, for $T_A > 1$, the PreBO phase of late arriving UE request overlaps with the TRA phase of early arriving UE requests. In this case, the newly (late) arriving UE requests distributed by the PreBO simply randomly content for individual preambles; while these preambles are also utilized in groups of two for the binary TRA.

2) Throughput and Delay Analysis: We analyze the throughput of PreBOTRA by evaluating the number of slots required to successfully complete all N UE requests. PreBOTRA distributes the N requests over Γ backoff slots, each with M preambles. Thus, the number $\Pi_{\gamma,\pi}$ of UE requests on a given preamble π in a given backoff slot γ is characterized by the pmf P_Π (7), resp. (9). The binary tree-based collision resolution is executed for these $\Pi_{\gamma,\pi}$ UE requests.

The expected number $f_{\text{ST}}(n)$ of slots required to complete the static binary tree-based collision resolution for n requests is given as [91]

$$f_{\text{ST}}(n) = \begin{cases} 1 & \text{if } n = 0 \\ 1 & \text{if } n = 1 \\ 5 & \text{if } n = 2 \\ 7.667 & \text{if } n = 3 \\ . & \\ 2.88n & \text{if } n = n. \end{cases} \tag{10}$$

The expected number $f_{\text{ST}}(n)$ of slots covers the initial transmission attempt of a given set of $\Pi_{\gamma,\pi}$ UE requests on preamble π in backoff slot γ, plus, if a collision occurs, the conflict resolution in the binary tree (with groups of two preambles) during the collision resolution. Thus, the expected number of slots required to serve the set of $\Pi_{\gamma,\pi}$ UE requests on a given preamble π in a given PreBO slot γ is $\sum_{n=0}^{N} P_\Pi(n) f_{\text{ST}}(n)$. Noting that a total of ΓM sets of UE requests (on the ΓM preambles across the Γ PreBO slots) need to be served, a mean number of $\Gamma M \sum_{n=0}^{N} P_\Pi(n) f_{\text{ST}}(n)$ slots are required to serve all sets of UE requests on one preamble. Each slot provides M preambles. Thus, a mean number of

$$S_{\text{PreBOTRA}} = \Gamma \sum_{n=0}^{N} P_\Pi(n) f_{\text{ST}}(n) \tag{11}$$

slots are required for the last set of UE requests to complete PreBOTRA. On average, a given UE request will only

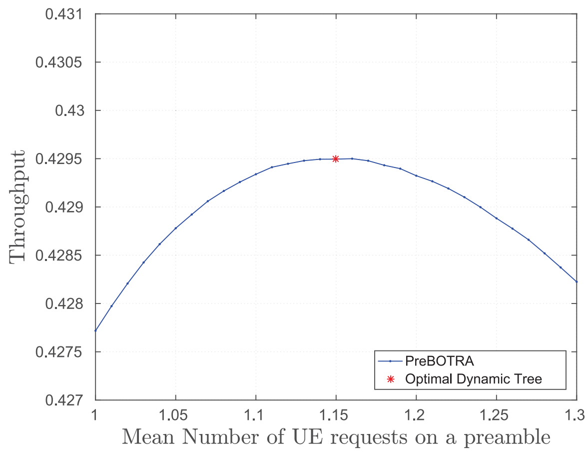

Fig. 5. Expected PreBOTRA throughput (13) as a function of the mean of $\Pi_{\gamma,\pi}$, i.e., of the mean number of UE requests on a preamble in a PreBO slot. Fixed parameters: $M = 54$ preambles, $N = 10\,000$ nodes. Setting the number Γ of PreBO slots according to (4) to achieve a mean number of 1.15 UE requests per preamble in a PreBO slot achieves the maximum expected throughput of 0.4295 (successful UE requests per preamble per slot) of the optimal dynamic tree [80].

experience half of this time duration as PreBOTRA delay. Thus, the average UE request delay in slots is

$$D = \frac{\Gamma}{2} \sum_{n=0}^{N} P_{\Pi}(n) f_{\mathrm{ST}}(n). \tag{12}$$

In order to derive the expected PreBOTRA throughput, we neglect that UE request are dropped when exceeding the number of transmission attempts permitted by LTE. As evaluated in Section VII, this is a reasonable assumption as the drop probabilities are typically very low. Thus, we consider that N UE requests are successfully served during the total PreBOTRA time span of S_{PreBOTRA} slots. Each slot has M preambles available. Hence, the expected throughput in successful UE requests per preamble per slot is

$$T = \frac{N}{\Gamma M \sum_{n=0}^{N} P_{\Pi}(n) f_{\mathrm{ST}}(n)}. \tag{13}$$

which simplifies with (4) to

$$T = \frac{1.15}{\sum_{n=0}^{N} P_{\Pi}(n) f_{\mathrm{ST}}(n)}. \tag{14}$$

In Fig. 5, we plot the expected throughput as a function of the mean number of UEs per preamble, i.e., we vary the mean of $\Pi_{\gamma,\pi}$ around 1.15. The plot verifies that setting the number of PreBO slots Γ according to (4) to achieve a mean of $\Pi_{\gamma,\pi}$ equal to 1.15 achieves the maximum expected throughput of 0.4295 successful UE request per slot. The plot also illustrates that small deviations of the mean of $\Pi_{\gamma,\pi}$ from 1.15 cause only minuscule throughput degradations.

B. DABTRA

Analogously to PreBOTRA, the overall DABTRA protocol is a concatenation of the DAB collision avoidance specified in [43] (and briefly summarized in Section IV-D) and the TRA collision resolution specified in Section V-B.

TABLE I
Summary of Main Model Notations

	System parameters (constants)
N	Number of devices (machines) = total number of UE requests
M	Number of preambles
T_A	Activation time period of the N UE requests
	Collision avoidance (Pre-backoff, PreBO)
Γ	Number (const.) of backoff slots with index $\gamma = 1, 2, \ldots, \Gamma$
B_γ	Number (rand. var.) of UEs in given backoff slot γ
$\Pi_{\gamma,\pi}$	Number (rand. var.) of UEs on given preamble π in given backoff slot γ

For protocol simplicity, similar to PreBOTRA, we let the TRA always start Γ slots after the beginning of the synchronous M2M arrivals. Alternative DABTRA variations could vary the start of the TRA phase, e.g., the TRA could start right away as soon as UE requests that have passed the DAB experience a collision on a preamble.

VII. PERFORMANCE EVALUATION

In this section, we compare the performance of two forms of the proposed hybrid collision avoidance-tree resolution random access, namely PreBOTRA and DABTRA, against existing benchmarks that employ either collision avoidance or tree resolution.

A. Evaluation Setup

We conducted the evaluations through MAC layer simulations of the standard LTE RACH system with a custom MATLAB discrete event simulator which is publicly available from https://github.com/tum-lkn/hyctra. We considered a maximum of eight transmission attempts for a given UE request and $M = 54$ preambles. For each combination of M2M traffic model and number of UE requests N, we simulated 100 independent replications, resulting in 95% confidence intervals that are smaller than 5% of the respective sample means. The confidence intervals are not plotted to avoid clutter.

B. Benchmarks

We have compared three benchmarks protocols, as summarized inTable II, with the PreBOTRA and DABTRA protocols. Generally, all protocols operate with the underlying standard LTE random access procedure with at most eight transmission attempts. The protocols without DAB do not employ access barring. The protocols without TRA back off uniformly over at most Γ slots after a collision. The LTE with PreBO benchmark invokes the PreBO from Section IV-A when synchronous arrivals are detected. This LTE with PreBO benchmark represents the PreBO collision avoidance focused approaches, as for instance examined in [47]. The LTE with DAB benchmark employs DAB for collision avoidance, as examined in [43] and [45]. The LTE with tree benchmark resolves collisions with a binary tree, as described in Section V. This LTE with tree benchmark represents the tree resolution focused approaches, as for instance examined in [60].

TABLE II
Summary of Evaluation Benchmarks With Theoretically Expected Maximum Throughput and Added Complexity With Respect to Standard LTE

Protocol	Description	Exp. Throughp.	Added Complexity
Benchmarks			
LTE+PreBO	LTE with PreBO [47]	$1/e \approx 0.367$	Synch. arrival detection
LTE+DAB	LTE with DAB [43], [45]	$1/e \approx 0.367$	ACB param. update in each slot
LTE+TRA	Tree for each collision resolution [60]	0.2	Collision based feedback
Hybrid Collision Avoidance—Tree Resolution			
PreBOTRA	Pre-Backoff /w tree, Section VI-A	0.4295	LTE /w PreBO + LTE /w Tree
DABTRA	DAB /w tree, Section IV-D	0.4295	LTE /w DAB + LTE /w Tree

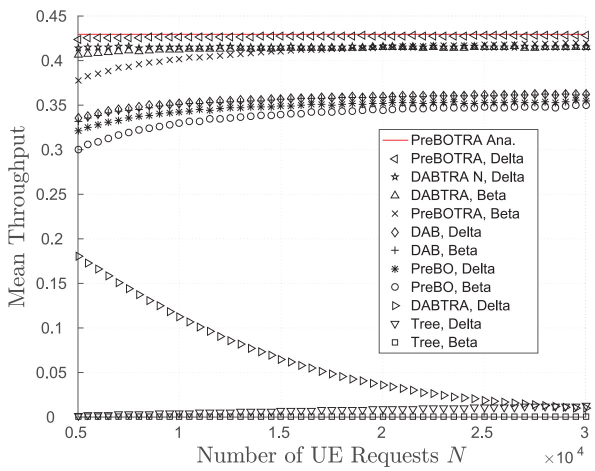

Fig. 6. Mean throughput, i.e., mean number of successful UE requests per preamble per slot, as a function of number of UE requests N arriving either in $T_A = 1$ slot (Delta arrival model) or over $T_A = 50$ slots (Beta arrival model). Fixed parameter: $M = 54$ preambles.

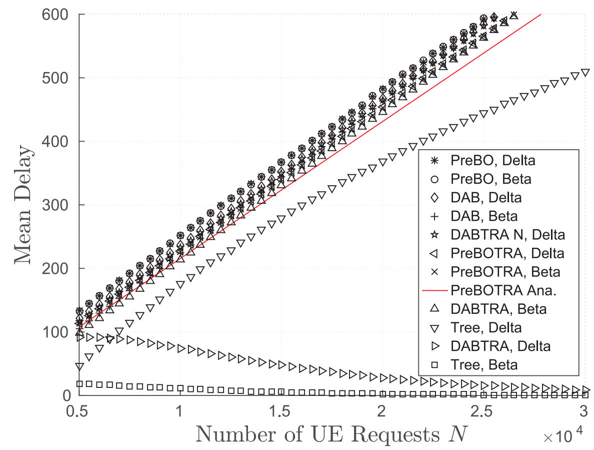

Fig. 7. Mean delay in slots as a function of number of UE requests N.

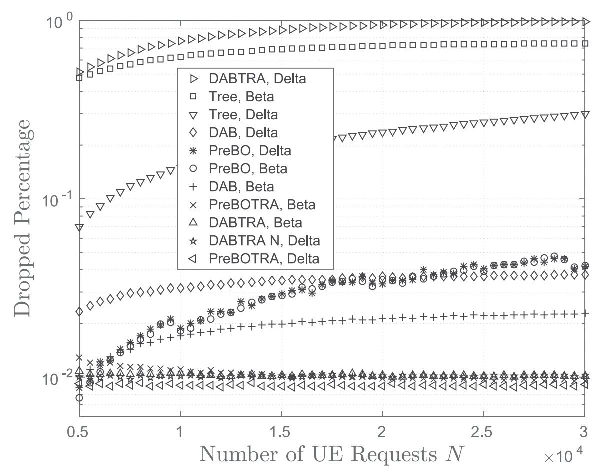

Fig. 8. UE request drop probability as a function of number of UE requests N.

C. Performance Metrics

We define the mean throughput as the number of UE requests N divided by the mean time period in slots from the starting instant of the synchronous M2M arrivals until all N requests are either successful or dropped. We define the mean delay as the mean time period in slots required to serve a UE request from the time instant of request generation (activation) until the request is either successfully transmitted or dropped. We define the UE request drop probability as the ratio of the number of dropped UE requests to the total number of N UE requests.

D. Evaluation Results

In Figs. 6–8, we plot the performance metrics obtained from simulations as a function of the number of UE requests N. We also plot the expected throughput [see (14)] and delay [see (12)] from the PreBOTRA analysis. We observe from Fig. 6 that for Delta arrivals, PreBOTRA essentially attains the theoretically expected maximum mean throughput of 0.4295. On the other hand, for Beta arrivals, PreBOTRA gives throughputs below 0.4 for relatively small numbers of UE requests, while the throughput approaches the theoretical maximum for large numbers of UE requests. As described in Section VI-A1, for simplicity, PreBOTRA always employs the PreBO interval Γ specified in (5), which assumes that all N UE requests are distributed over the Γ PreBO slots. However, for an activation time period $T_A > 1$, the N UE requests are distributed by the PreBO over more than Γ slots (see Section VI-A1). Thus, the mean number of UE requests on a preamble is lower than the optimal 1.15, leading to the throughput degradation outlined in Section VI-A2 and illustrated in Fig. 5. That is, we are operating to the left of the optimal dynamic tree point in Fig. 5. Increasing the number of UE requests N for fixed activation time period T_A moves the operating point to the right, i.e., we are approaching the optimal dynamic tree point in Fig. 5 from the left.

Turning to DABTRA, we observe from Fig. 6 low throughputs for Delta arrivals. By adapting the access barring based on the observed history, the original DAB version reacts slowly to the sudden Delta arrivals, leading to excessive congestion on the preambles, and accordingly high drop probabilities (see Fig. 8) and consequently low throughput. A modified DABTRA version that is provided with information about the N Delta arrivals, denoted as "DABTRA N" in Fig. 6, achieves nearly the same throughput as PreBOTRA for Delta arrivals. The collision avoidance provided by DABTRA N effectively reduces the preamble congestion. However, the Delta arrivals are not optimally shaped (with the optimum Γ, see Section VI-A) for TRA, leading to slightly lower throughput than PreBOTRA. For Beta arrivals, the original DABTRA gives slightly higher throughput than PreBOTRA for low UE request numbers N, while both PreBOTRA and DABTRA achieve essentially the same throughput for high UE request numbers N. The more gradual Beta arrivals (compared to the sudden Delta arrivals) give DAB sufficient time to dynamically adapt the access barring, providing effective collision resolution. In practical systems, perfectly synchronized arrivals are typically due to some system reset, for which the modified DAB can be activated, or the arrivals are spread out over several slots (which have on the order of 10 ms duration). Thus, the performance of the modified DABTRA for Delta arrivals and the original DABTRA for Beta arrivals can be considered to reflect the DABTRA performance possible in practical systems.

We observe from Fig. 6 that the benchmarks employing only collision avoidance, followed by the conventional LTE collision resolution with uniform backoff, i.e., LTE+PreBO and LTE+DAB, achieve very similar throughput that approaches the theoretical maximum of $1/e$ for increasing number of UE requests N. In contrast, we observe from Fig. 6 that the benchmark without collision avoidance, i.e., LTE+Tree gives very low throughput below 0.02. These results underscore the importance of collision avoidance for synchronous M2M arrivals. Without collision avoidance, the synchronous M2M arrivals cause excessive congestion on the preambles. The tree resolution cannot resolve the resulting excessive collisions within the LTE retransmission limit (of eight in the considered scenario), leading to high drop probabilities (see Fig. 8). On the other hand, the LTE+PreBO and LTE+DAB results indicate that after collision avoidance, the standard LTE collision resolution can achieve moderate throughput levels. Adding the tree resolution after the collision avoidance to form the hybrid collision avoidance-tree collision resolution protocols significantly increases the throughput levels (compared to the benchmarks employing only collision avoidance with standard LTE collision resolution), as indicated by the PreBOTRA and DABTRA results.

Importantly, we observe from Fig. 7 that the increased throughput with the hybrid collision avoidance-tree collision resolution protocols (compared to collision avoidance with standard LTE collision resolution) does *not* come at the expense of increased delays. Rather, we observe that the mean delays of PreBOTRA and DABTRA are very slightly lower than the delays of the collision avoidance benchmarks LTE+PreBO and LTE+DAB. This is because the tree resolution optimizes the utilization of the preambles in the collision resolution.

We observe from Fig. 8 that the hybrid collision avoidance-tree collision resolution protocols achieve consistently low drop probabilities around 10^{-2} in the considered scenario with an LTE limit of at most eight transmission attempts. In order to assess the effects of increasing the number of transmission attempts on PreBOTRA, we have run simulations with $N = 10\,000$ Delta arrivals for increasing numbers of transmission attempts. In particular, for 8, 12, 16, and 20 transmission attempts, the mean drop probabilities are 0.009, $5 \cdot 10^{-4}$, $5 \cdot 10^{-5}$, and $2 \cdot 10^{-6}$, respectively, while the mean delays are 227, 230, 231, and 231 slots. These results indicate that the required level of reliability can be set via the maximum number of permitted transmission attempts. The results also indicate that this adjustment of the reliability level has negligible impact on the mean delay.

VIII. CONCLUSION

We have introduced the class of hybrid collision avoidance-tree resolution protocols for the MAC of machine-to-machine traffic. Specifically, the PreBOTRA protocol combines PreBO with tree collision resolution, while the DABTRA protocol combines DAB with tree collision resolution. These protocols are based on knowledge of the number of communicating machines (devices), which is commonly available for wireless communication systems on board of aircraft. Our extensive evaluations indicate that a collision avoidance mechanism is critically important for an effective MAC protocol for bursty M2M traffic. The evaluations have also demonstrated that PreBOTRA and DABTRA achieve significantly higher throughput, namely up to 0.4295 successful requests per slot per preamble, than existing benchmarks that only employ collision avoidance (but no tree collision resolution).

There are several interesting directions for future research on MAC protocols for M2M traffic in aeronautical settings. One important direction is to explore delay reductions, e.g., by separating the collision avoidance and tree collision resolution in the preamble domain (rather than in time, as considered in the present study). Another direction is to develop mathematical models for Beta distributed M2M traffic in hybrid collision avoidance-tree resolution MAC protocols.

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