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On Random Access Channel Performance and M2M Support in Standalone LTE Unlicensed

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***Abstract*—Next generation telecommunication systems are required to efficiently support orders of magnitude larger amount of devices per cell than the current LTE networks. This requirement is causing major design challenges for the Random Access Channel (RACH), especially for Machine-to-Machine (M2M) applications. On the other hand, due to the increasing spectrum demands, LTE vendors are exploring unlicensed spectrum. For example, MulteFire has been recently standardized as an LTE-based technology for standalone deployment in unlicensed 5GHz frequency bands. It is reasonable to expect that the coexistence with Wi-Fi and standalone LTE in the unlicensed spectrum, will amplify Random Access problem and worsen RACH performance. Henceforth, in this paper, we quantify the Wi-Fi–LTE coexistence and its impact on the RACH performance. We consider a synchronized activation of a large amount of UEs in an MulteFire/LTE unlicensed cell, and analyze the time it takes to connect all of them to the base station. Our results confirm that the presence of Wi-Fi substantially degrades RACH performance, with an increase of almost 50% per additional Wi-Fi station. Furthermore, we illustrate applications of our evaluation for RACH resource dimensioning and network planning.**

***Index Terms*—LTE; MulteFire; Random Access; M2M**

I. Introduction

Evolution of cellular network standards towards 5G brings a great number of novel challenges to be addressed in the future designs [1]. First challenge on the way to 5G is the growing spectrum demand. To address it, there are ongoing developments of LTE-Licensed Assisted Access (LAA), enabling an LTE licensed network to offload data traffic to unlicensed spectrum as a further expansion of Carrier Aggregation (CA). Complementary to LAA, there exist recent standardization efforts to develop *standalone* LTE in the unlicensed spectrum. For instance, MulteFire Alliance has just released a technical report and first draft of the standard [2] for such technology. In contrast to LAA, MulteFire assumes that not only data, but also *control channels* are shifted to the unlicensed spectrum. This makes MulteFire independent on the licensed carrier, and implementable as a local, standalone solution.

Apart from the spectrum challenge, 5G systems are envisioned to support novel applications, such as Machine-to-Machine (M2M). While there is no clear consensus if M2M devices can be deployed in LAA or MulteFire networks, license-free band usage is possible for certain indoor M2M installation scenarios, e.g., production sites or intra-aircraft communication [1], [3]. However, M2M applications feature a massive amount of devices in a single cell, which are not supported by the currently standardized LTE systems. In particular, massive M2M devices put a strain on LTE Random Access procedure, creating a notorious Random Access Channel (RACH) bottleneck, especially in the case of a highly synchronized traffic, typical for M2M devices [4].

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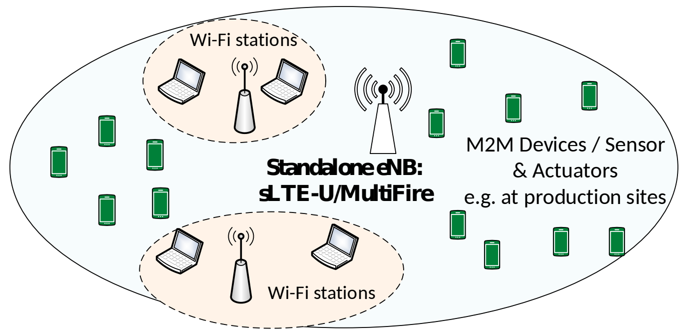


Fig. 1: Scenario: N M2M UEs, n Wi-Fi stations and one standalone LTE eNB in close proximity, operating in unlicensed 5 GHz band.

For standalone LTE/MulteFire deployments in unlicensed bands, the problem of RACH overload might be even amplified due to the underlying coexistence with other wireless technologies – primarily Wi-Fi. In its conventional form, LTE and Wi-Fi are incompatible in terms of medium access [5]. Wi-Fi has been developed specifically for unlicensed bands, and uses a Carrier Sense Multiple Access (CSMA/CA) scheme and back-offs to share the medium with other stations. On the contrary, LTE has been developed for licensed bands, with no need of medium sharing. Therefore, LTE-LAA and MulteFire introduce channel sensing – Listen Before Talk (LBT) [6]. With LBT, LTE network contends with co-located Wi-Fi stations for the medium access, with the goal to ensure fair coexistence. However, it is still an open question how this contention might influence the RACH performance, and, hence, whether LTE in unlicensed spectrum can support M2M.

A. Contributions

In this paper, we analyse and quantify the impact of Wi-Fi contention with LTE on the performance of RACH. Our scenario, inspired by M2M use case, is a standalone LTE unlicensed network with a large number of connected devices, co-located with a Wi-Fi network as depicted in Fig. 1. Both Wi-Fi and LTE share the same 5 GHz unlicensed spectrum. Core contributions of our paper are: (i) analytical approximation model for computing the *burst resulution time*: total time to connect a burst of M2M UEs to the network. Our analysis merges a model of the contention between LTE and Wi-Fi, and LTE RACH performance model. (ii) Comprehensive simulations, quantifying the implications of coexistence on RACH performance.

B. Related Work

Many studies have been conducted to investigate the limitations of conventional LTE RACH for massive M2M [7]. Multiple potential solutions have been proposed: dynamic adjustment of contention parameters (barring factor, back-off) [4], [8], load-adaptive and quality-of-service-aware RACH resource allocation [4], [9]. Also, methods for channel utilization improvement and fast collision resolution, such as tree algorithms or distributed queuing have been proposed in [3], [4]. However, all of the related works have considered only classical LTE deployment in a licensed band.

Secondly, the introduction of LTE unlicensed and LTE-LAA has created a broad interest in schemes to ensure *fair coexistence* between unlicensed LTE and other technologies using the 5 GHz spectrum. Multiple studies analysing different outdoor and indoor scenarios, and various coexistence methods have been performed [6], [10], [11]. Most of them consider the coexistence as a medium access problem, and analyse the performance by the means of the Markov chain analysis, typical for contention-based access [12]–[14]. Additionally, spectral efficiency-based approach to defining the fair coexistent has been studied in [15].

In summary, while there exist studies addressing LTE and Wi-Fi coexistence in unlicensed bands, all of them are focusing on the impact of coexistence on LTE and Wi-Fi data channels. To the best knowledge of the authors, this is the first work considering how the coexistence impacts a *control channel performances*, in particular Random Access Channel.

The paper is outlined as follows. We present our analytical system model and explain the underlying technology assumptions in Sec. II, III. In Sec. IV, we validate the analytical model, and present simulation results. Finally, we conclude with the discussion and outlook in Sec. V

II. Coexistence of sLTE-U and Wi-Fi

We consider a scenario with N UEs deployed within one standalone LTE Unlicensed (sLTE-U)[1] small cell spanned by a single eNB. UEs are colocated with n Wi-Fi stations and operate on the same frequency in 5 GHz, see Fig. 1. To ensure fair coexistence of LTE and Wi-Fi, eNB utilizes Listen Before Talk (LBT) in a Wi-Fi like fashion [6]. We assume a cat. 4 LBT (recommended by 3GPP), with exponential back-off and variable contention window (CW) [6], [11, 4.8.3.2 Option B].

[1]We refer to standalone LTE unlicesed with a non-conventional abbreviation sLTE-U to emphasize that MulteFire is only an example and our approach is generalizable beyond a particular technology. On the same time, we use sLTE-U to avoid confusion with LTE-U standard based on 3GPP rel. 12.

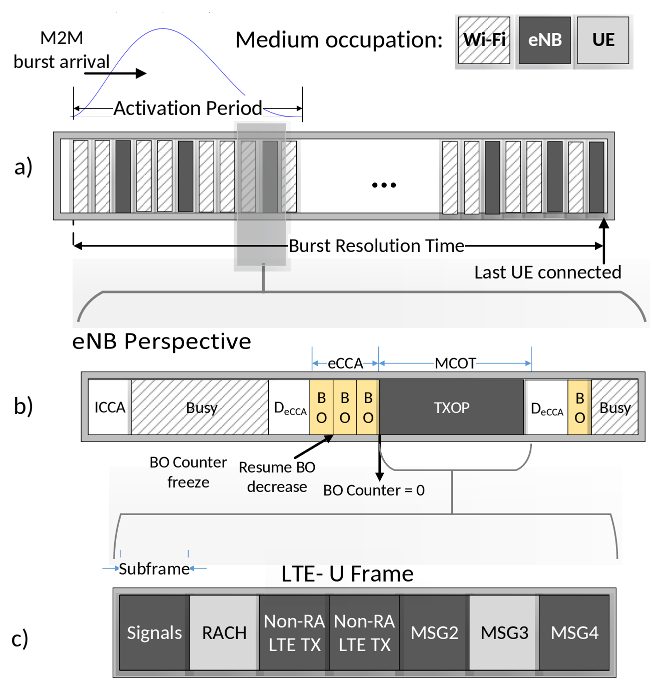


Fig. 2: Exemplary timeline: (a) RACH and burst arrivals; (b) eNB LBT procedure; (c) sLTE-U frame.

Details of an exemplary LBT procedure are depicted in Fig. 2b. A transmission is initiated if the channel has been sensed idle for a Initial Clear Channel Assessment (CCA) (ICCA) of duration similar to Wi-Fi's Distributed Inter-Frame Space (DIFS). Otherwise, if the channel is busy, a random back-off counter is drawn, and the channel has to be sensed idle again for a defer period $\mathrm{D_{eCCA}}$ of similar length to ICCA. For every extended CCA (eCCA) duration that the channel is sensed idle, the counter is decremented. If the channel is found to be busy, the counter freezes and is only resumed after another $\mathrm{D_{eCCA}}$. Once the counter reaches zero, the station obtains the Transmission Opportunity (TXOP), and captures the medium by transmitting for up to the Maximum Channel Occupancy Time (MCOT) of $T_{\max}$. If multiple stations reach the end of their back-off counter at the same time, a collision occurs, and both respective transmissions are lost (we assume no recovery is possible).

We consider all Wi-Fi stations to use the classical Distributed Coordination Function (DCF) with CSMA/CA and binary slotted exponential back-off [16]. Moreover, we assume a scenario of *fair coexistence* between Wi-Fi and sLTE-U. While, in general, fair co-existence can be defined in different ways, as equal spectral efficiency or equal cross-impact of technologies [15], [17], here, we adopt the definition of fairness as equal steady-state shares of medium access time [12]. This implies that the contention parameters of sLTE-U and Wi-Fi are configured similarly [17], and, hence, we can approximate the set-up by treating n Wi-Fi stations and one eNB as a homogeneous set of $n+1$ stations. Furthermore, we further assume a *saturation condition*, where all stations continuously contend for medium, and fully utilize respective TXOPs. Note that both homogeneity and saturation assumptions are common in the literature and the model can be easily extended to relax them [12], [18].

III. System Model

In contrast to LAA, standalone LTE, e.g., MulteFire, transmits both data and signaling in the unlicensed band. Naturally, the underlying LTE–Wi-Fi contention impacts LTE signaling procedures, and delays the connection establishment. In this section, we describe our model for sLTE-U connection establishment, which is based on the works of Bianchi [18] and Wei *et. al* [19]. In III-A, we explain the Markov chain model for the Wi-Fi/sLTE-U contention, and in III-B, we outline the performance model of preamble contention on RACH. After that, we merge the two models in III-E.

A. Markov Chain Medium Access Model

Given the preliminaries stated above, the behavior of an individual station (either Wi-Fi or eNB) can be modeled as a Markov Chain [18]. In the following we outline the model and its usage, without going into the details, since the approach is well known and commonly used in the literature for modeling of contention-based access [12], [18].

The behavior of a station is comprised of discrete states (i, j), representing different stages of the back-off, where $i \in [0, m]$ is the transmission attempt (back-off stage), and $j \in [0, W_i - 1]$ is the back-off counter value. W_i denotes the contention window size at the back-off stage i. Starting from the mth back-off stage, back-off window remains constant. Transitions between states occur at every *slot*. A slot is defined by two consecutive decreases of the back-off counter, thus, its length δ is a random variable (e.g., when a station senses the channel busy, the back-off counter is frozen).

We define τ as the expected channel access probability, and p as the expected collision probability in a given slot. In the steady state, both p and τ are independent of the back-off stage. Transition probabilities for all the states in a Markov chain can be computed as a function of the back-off stage i, back-off counter j, initial back-off window size W_0, and collision probability p [18]. Next, these probabilities are used to obtain the steady-state probabilities $p_{i,j}$ for all states, and, using normalization condition, we obtain the system of equations:

$$\tau = \frac{2(1-2p)}{(1-2p)(W_0+1)+pW_0(1-2p)^m}, \quad (1)$$

$$p = 1-(1-\tau)^n. \quad (2)$$

After solving the equations for τ numerically, probabilities of at least one and exactly one transmission on the channel, denoted respectively P_{tx} and P_{s}, are computed as:

$$P_{\text{tx}} = 1-(1-\tau)^{n+1}, \quad (3)$$

$$P_{\text{s}} = \frac{(n+1)\tau(1-\tau)^n}{P_{\text{tx}}}. \quad (4)$$

Eqns. (3), (4) are used to compute the expected slot length:

$$\mathbb{E}[\delta] = (1-P_{\text{tx}})\sigma + P_{\text{tx}}P_{\text{s}}T_{\text{s}} + P_{\text{tx}}(1-P_{\text{s}})T_{\text{c}}. \quad (5)$$

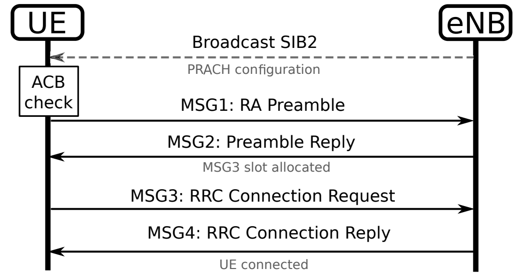


Fig. 3: Protocol and messages of LTE Random Access Procedure.

Here, σ is the empty slot length, and the values for T_{s} and T_{c} denote the time duration that the medium is sensed busy due to a successful transmission or a collision on the medium, respectively. In addition to the duration of channel capture, T_{s} also includes the overhead of Inter-Frame Spaces and ACKs:

$$T_{\text{s}} = T_{\max} + \text{DIFS} + \text{SIFS} + \text{ACK}. \quad (6)$$

This accounts for the fact that prior to every successful transmission the channel needs to be sensed idle for DIFS. Also, it can only be sensed idle again from another station after Short InterFrame Space (SIFS) and ACK have been transmitted (in the case of Wi-Fi). On the other hand, in case of a collision, we have

$$T_{\text{c}} = T_{\max} + \text{DIFS}, \quad (7)$$

because the colliding stations are assumed to continue transmission for a full duration $T_{\max}$. Furthermore, in case of collision no ACK is transmitted such that the channel can be sensed idle directly from the end of the TXOP on.

B. Connection Establishment in sLTE-U

Having stated the modeling preliminaries of the Wi-Fi and sLTE-U contention, we now proceed by describing the RACH performance model. The steps for establishing a connection of a UE to the network are initial cell search and random access procedure [20]. MultiFire RA procedure is based on the 3GPP LTE four-step procedure [2] as illustrated in Fig. 3.

Once eNB obtains a TXOP, one LTE frame consisting of multiple sub-frames is sent. We assume that eNB fully occupies the medium for MCOT $T_{\max}$. Compliant with the MulteFire Discovery Reference Signals (DRS) scheme, we assume that at the beginning of the first sub-frame, signals to provide UEs with the necessary information to connect to the network are sent. Among them. the Physical Random Access Channel (RACH) (PRACH) configuration index: preamble contention parameters, such as Access Class Barring (ACB) factor p_{acb}, and the location of the PRACH sub-frame.

UE proceeds with sending a randomly chosen preamble (codeword) in MSG1, and receives MSG2 as an eNB reply, containing the timing and location of the sub-frame for MSG3 for every received ("activated") preamble. The eNB is only able to detect whether a particular preamble has been activated, but not how many UEs have sent it. Hence, if two or more UEs choose the same preamble at MSG1, eNB assigns them the same uplink grant, and their connection requests (MSG3s) will collide. If the connection requests collide, no MSG4 is received from the eNB, and the UEs will re-attempt sending the preambles after a random back-off time. We assume that all RA procedure handshake, MSG1 to MSG4, occurs within one TXOP of an eNB (exemplary frame structure in Fig. 2c), and there are enough resources in Physical Downlink Control Channel (PDCCH) for MSG2. For tractability, we also assume throughout the analytical model that no LBT for UEs in UL (RACH and MSG3) is necessary. This assumption is later relaxed in Sec. IV-D.

C. Burst Connection Requests Arrival

As a RACH traffic model, we consider a burst arrivals scenario for connection establishment requests, i.e., near synchronous activation of a large number of UEs in a cell. This scenario is common for M2M communication, e.g., network recovery after a power outage, or alarm reporting in emergency situations [3], [7], [8]. All N M2M UEs are activated in a simultaneous manner over activation time T_A according to a beta distribution [8]:

$$g(t_a^i) = \frac{(t_a^i)^{\alpha-1}(T_A - t_a^i)^{\beta-1}}{T_A^{\alpha+\beta-2}\mathcal{B}(\alpha,\beta)}, \quad 0 \le t_a^i \le T_A, \tag{8}$$

where t_a^i is the activation time of UE i.

Burst arrivals [4] can cause overload in the channel, and result in very high delay and connection request drop probabilities [4], [9]. Standardized LTE method to mitigate overload effects is ACB. Prior to every transmission a device draws a random number from a set $\mathcal{X}$ and compares it to a broadcasted value p_{acb} called ACB factor. If the number drawn is smaller than $p_{\text{acb}} \cdot |\mathcal{X}|$, it proceeds to access the medium, otherwise it retries in the next slot, going through ACB again (geometric back-off).

D. Preamble Contention Model

To analyze the performance of preamble contention, we apply a simplified drift approximation model proposed by Wei *et al.* [19]. We consider discrete time divided into *PRACH slots*. In contrast to [19], in our scenario PRACH slots have *variable length* T_{RA} because of the contention between eNB and Wi-Fi. Assuming the activation pattern given by (8), expected number of UEs activated in a PRACH slot i is given by $\lambda_i = N\int_{(i-1)\mathbb{E}[T_{\text{RA}}]}^{i\mathbb{E}[T_{\text{RA}}]} g(t)dt$.

The current backlog of the system, i.e., the number of activated but not yet connected UEs is described by its expected value q_i, representing the expected number of backlogged UEs at the slot i. We further subdivide the state transition into an activation and a transmission step. The activation step (addition of the newly activated UEs) is computed by adding the new arrivals $q_i' = q_{i-1} + \lambda_i$. Next, the expected number of successful UEs is computed as a function of the barring factor $p_{\text{acb,i}}$ and the number of available preambles per slot M [19]:

$$\Delta q_i = \underbrace{p_{\text{acb,i}} q_i'}_{\text{non-barred UEs}} \left(1 - \frac{1}{M}\right)^{p_{\text{acb,i}} q_i' - 1}. \tag{9}$$

Henceforth, the transmission step is modeled as an addition $q_i = q_i' + \Delta q_i$.

Finally, we aim at determining the *burst resolution time* T_{BR}^s, i.e., the time needed to connect all N UEs to the network (expressed in units of PRACH slot length). Given the backlog state of the system q_i, we can compute the expected T_{BR}^s with arbitrary precision ϵ iteratively with $t \to \infty$:

$$\mathbb{E}[T_{\text{BR}}^s] = i \text{ [PRACH slots]} \quad \text{if } q_i - \epsilon \le 0. \tag{10}$$

E. Merging Models: Burst Resolution Time

For sLTE-U, PRACH slot length T_{RA}, and, hence, the absolute periodicity of PRACH sub-frames, is a random variable, and its expected value depends on the medium access contention between eNB and Wi-Fi stations, outlined in Sec. III-A.

The steady-stated medium access parameters derived from the Markov chain model, can be used to obtain the number of slots between two successful channel captures of eNB, denoted as T_{tx}'. The probability that there is no slot between two transmissions of the same station, i.e., it draws a zero backoff counter and retransmits directly, equals $s = \tau(1-p)$. The probability mass function of T_{tx}' is $f_{T_{\text{tx}}'}(x) = (1-s)^x s$, which is a geometric distribution, whose expected value is found as:

$$\mathbb{E}[T_{\text{tx}}'] = \sum_{x=0}^{\infty} f_{T_{\text{tx}}'} x = \frac{1-s}{s}. \tag{11}$$

Assuming a PRACH configuration corresponding to one PRACH per eNB frame, we obtain expected RACH slot length $\mathbb{E}[T_{\text{RA}}]$ using Eqns. (5), (11) as:

$$\mathbb{E}[T_{\text{RA}}] = \mathbb{E}[\delta]\frac{1-\tau(1-p)}{\tau(1-p)} + T_{\max}. \tag{12}$$

Finally, in order to find the expectation of the absolute value of the burst resolution time (in seconds), denoted as T_{BR}, we use the expectation of it in PRACH slots $\mathbb{E}[T_{\text{BR}}^s]$ and the expected PRACH slot length $\mathbb{E}[T_{\text{RA}}]$ obtained via Eqns. (10) and (11) respectively. Assuming T_{BR}^s and T_{RA} are independent, we get[2]:

$$\mathbb{E}[T_{\text{BR}}] = \mathbb{E}[T_{\text{BR}}^s]\left(\mathbb{E}[\delta]\frac{1-\tau(1-p)}{\tau(1-p)} + T_{\max}\right) \quad \text{[s]}. \tag{13}$$

IV. Performance Evaluation

A. Evaluation Setup

We have implemented a detailed MAC-layer simulation model for the Random Access (RA) procedure in a sLTE-U Network with the event-based OMNeT++ framework (C++) [21]. Processing of statistics has been done with SciPy [22] libraries. Results are plotted with a 95% confidence interval. If not stated otherwise, the simulation follows the assumptions as presented in II, III. The parameters of the simulations are summarized in Tab. I.

We simulate with both a static and optimal dynamic ACB factor (p_{acb}) $p_{\text{acb,i}} = \min(1, \frac{M}{q_i})$ with q_i being the number

[2] In general, T_{BR}^s and T_{RA} are correlated because of λ_i. However, the independence assumption is accurate for typical bursts with $T_{\text{BR}} \gg T_A$.

TABLE I: Simulation Parameters.

Parameter	Range/Value
Variable Parameters	
Number of Wi-Fi stations n	0 - 25
Number of UEs N	100 - 10000
Activation period T_{A}	0.1 - 10 s
Number of preambles M	25, 54 (default)
Fixed Parameters	
MCOT for a specific scenario ($T_{\max}$)	7 ms
σ / eCCA slot duration	9 µs [6], [16]
DIFS / ICCA Defer period eCCA ($\mathrm{D_{eCCA}}$)	34 µs [6], [16]
SIFS	16 µs [16]
ACK length	14 bytes
W_0	32 [18]
m	5 [18]
Air propagation delay	1 µs

of backlogged UEs at PRACH slot i. Simulation runs with a static factor are used for model validation. We choose to use the optimal factor to study coexistence, because there exist schemes which approximate it also for practical scenarios [8].

B. Model Validation

First, we compare the analytic model proposed in Sec. III with the simulative results. For model validation, we set the number of preambles within the network to $M = 25$ and use a static ACB factor.

We compare analytical and simulation results for burst resolution time T_{BR} vs. number of Wi-Fi stations n in Fig. 4a and observe the values predicted by the model match with the simulation within the 95 % confidence intervals down to $T_A = 5$s. For small activation times $T_A \leq 1$s and large number of Wi-Fi stations $n > 15$, we observe that the analysis is overly pessimistic.

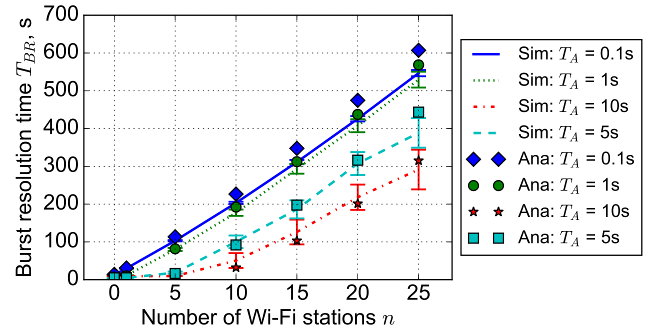
C. Impact of Coexistence on Random Access Performance

Now we show the impact of the medium access contention between one eNB and n Wi-Fi station on RACH performance.

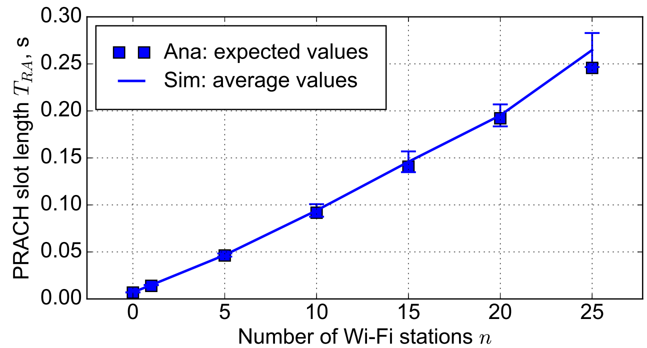
Fig. 5a shows burst resolution time as a function of the number of UEs N for varying number of Wi-Fi stations n. Clearly, T_{BR} rapidly increases with n. For example, at $N = 1000$ UEs, T_{BR} grows from 0.37s for $n = 0$ (no contention) to 13.7s for $n = 25$, which is a 37 times increase. Dividing by 25 Wi-Fi stations, one finds an average increase of almost 50 % per additional station.

However, increasing n only has a clear effect on T_{BR} when the system already operates at maximum in terms of intensity of access requests preamble. We introduce the notion of a stressed system. If $T_{\mathrm{BR}} - T_{\mathrm{A}} > 0$, we have a stressed system, if $T_{\mathrm{BR}} - T_{\mathrm{A}} \leq 0$, the system is unstressed. We plot the difference between T_{BR} and T_{A} in Fig. 5b, to show the influence of n on burst resolution time.

For a stressed system, increasing n directly translates into higher T_{BR}. The reason lies in an increased PRACH slot length due to contention (see Fig. 4b), hence, increasing n decreases the number of available PRACH slots per second.



(a) Burst resolution time T_{BR} vs. n for various T_A. Static $p_{\mathrm{acb}} = 0.2$, $T_{\max}$ = 7ms, $N = 1000$.



(b) PRACH slot length T_{RA} vs. n; $N = 1000$, $T_{\mathrm{A}} = 0.1$s.

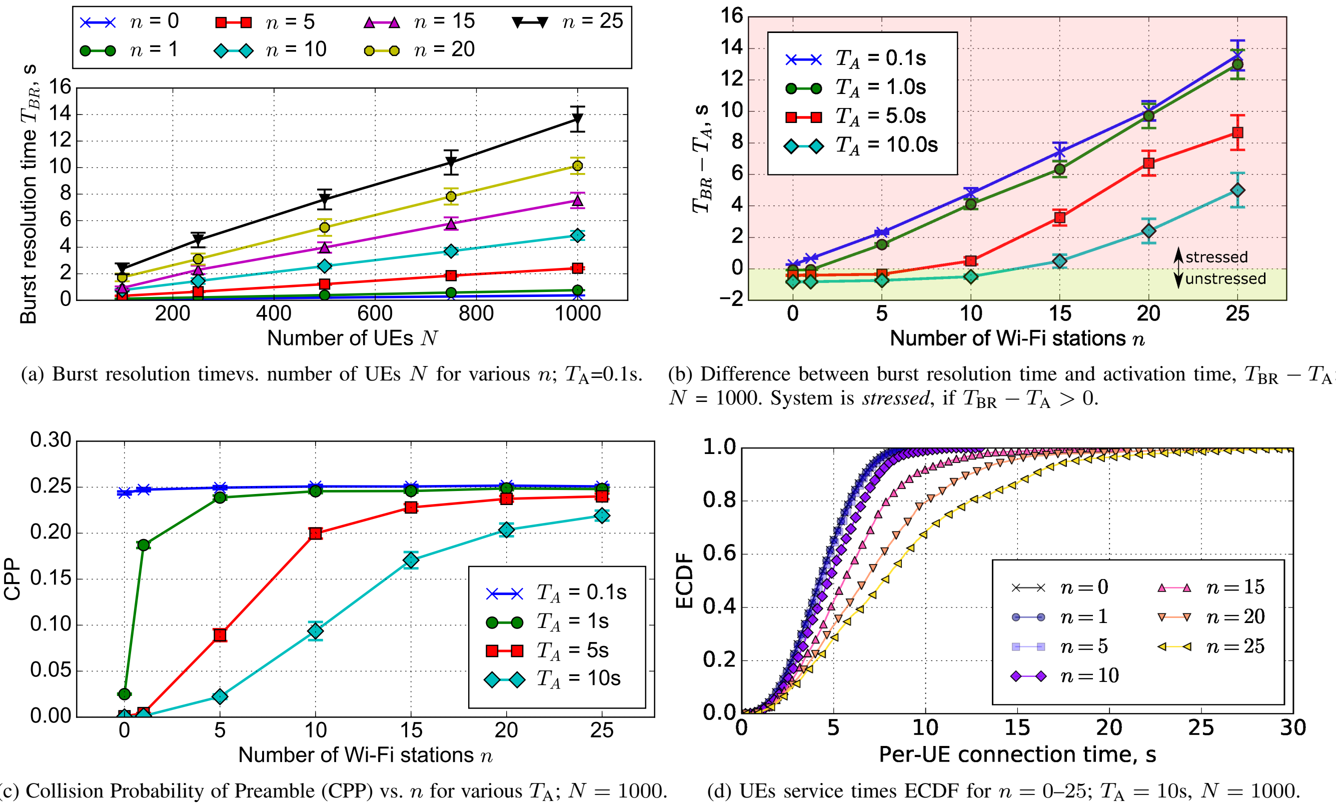
Fig. 4: Model validation: comparison of simulation and analysis.

If, however, a system is in unstressed state, n can be increased without great effect on T_{BR}, as the behavior of cyan curve for $T_A = 10$s illustrates in Fig. 5b. This is related to the amount of preamble collisions within one PRACH slot. To quantify this amount, we can look at the Collision Probability of Preamble (CPP) in Fig. 5c, defined as the ratio between the number of preambles activated by more than one UE and the total number of available preambles M. As we use optimal ACB factor, which maximizes the number of successfully transmitted preambles, we observe an asymptotic limit for CPP. Whenever CPP gets close to that value, the system is stressed; otherwise the system is unstressed and, hence, UEs in a cell can be supported efficiently.

We further provide an overview on the Empirical Cumulative Distribution Function (ECDF) of individual UEs' service time in Fig. 5d. An increase in n leads to a decreased slope and an increase of the maximum service time, i.e., the service time where the probability reaches one. This further confirms our previous observation on T_{BR}. We observe that all plots in Fig. 5d show linear behavior up to a specific probability, which initially lies close to one for $n = 0$ and then starts to decrease with growing n.

D. Listen-Before Talk prior to MSG3 Uplink

Finally, since LBT for UL transmissions is likely to be the regulatory requirement LTE Unlicensed realizations [2], [5], we investigate the influence of LBT before uplink MSG3 transmission by UEs.



(a) Burst resolution timevs. number of UEs N for various n; T_{A}=0.1s.

(b) Difference between burst resolution time and activation time, $T_{\mathrm{BR}} - T_{\mathrm{A}}$; N = 1000. System is *stressed*, if $T_{\mathrm{BR}} - T_{\mathrm{A}} > 0$.

(c) Collision Probability of Preamble (CPP) vs. n for various T_{A}; $N = 1000$.

(d) UEs service times ECDF for $n = 0$–25; $T_{\mathrm{A}} = 10$s, $N = 1000$.

Fig. 5: Impact of coexistence on RACH performance.

For that, we relax the saturation assumption that eNB continuously occupies its TXOP, and allow an idle pause in the medium occupation, just before MSG3 sub-frame. During the pause, eNB remains idle, and, hence, releases the channel and Wi-Fi stations can potentially capture it. Intuitively, the pause represents the time when *no DL or UL transmission is occurring in the LTE network*. The pause can last up to multiple sub-frames. We present illustrative results for the eNB pause $T_p = 34\mu s$ (one DIFS), and $T_p = 68\mu s$ in Fig. 6. For values smaller than $T_{\mathrm{p}} < 34\,\mu\mathrm{s}$ no channel capture by Wi-Fi stations is possible. Following MulteFire assumptions, we consider that UEs only have to perform a one shot CCA. If the channel is sensed idle, UEs start to transmit and LTE resumes to capture the channel until the end of eNB's TXOP. If UEs sense the channel busy, because of Wi-Fi capture, MSG3s fail and UE needs to restart the RA procedure, since the uplink grant has to be re-allocated.

We observe in Fig. 6 that a length of $T_{\mathrm{p}} = 34\mu s$ increases T_{BR} by up to 50 %, with the higher increase for larger number of Wi-Fi stations n. This is a moderate increase caused only by collisions between Wi-Fi and UEs. However, with $T_{\mathrm{p}} = 68\mu s$ we observe that the T_{BR} is doubled already for $n = 10$ Wi-Fi stations. With $n = 25$, T_{BR} drastically increases 6.88 times, from ≈ 40 s for no pause up to ≈ 275s.

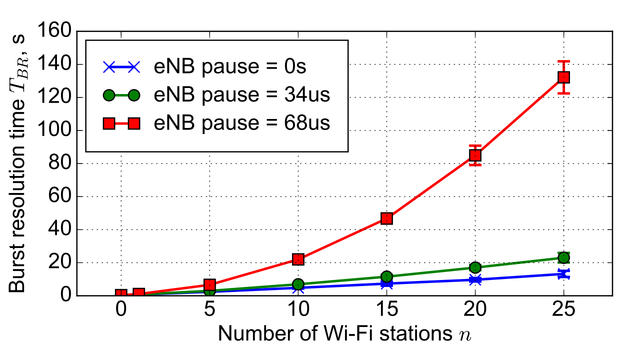


Fig. 6: T_{BR} vs. n for varying idle pause T_{p}; $N = 1000$, $T_A = 10$s.

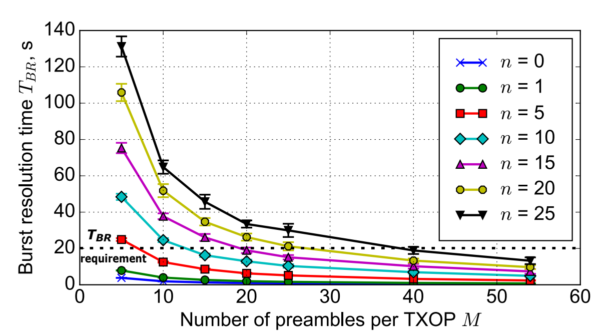


Fig. 7: T_{BR} vs. number of preambles M available per TXOP. $N = 1000$; $T_{\mathrm{A}} = 0.1$s; exemplary T_{BR} requirement of $T'_{\mathrm{BR}} = 20$ s.

V. Discussion and Conclusions

In this paper, we have presented a performance evaluation of the Random Access Channel of standalone LTE network in an unlicensed band. Up to now, standalone LTE-U technology is only represented by recently specified MulteFire standard, but our evaluation methodology is not bound to a specific technology. We have studied a scenario with one eNB coexisting with multiple active Wi-Fi stations, and evaluated the impact of Wi-Fi–eNB contention on the burst resolution time for a semi-synchronous arrival of a large number of M2M connection requests to the eNB. The evaluation included an analytical model and comprehensive simulations.

Most important findings of our evaluation are: (1) burst resolution time is heavily impacted by the contention with Wi-Fi, increasing by ≈ 50 % per every added Wi-Fi station. (2) Wi-Fi contention increases collision probability of a preamble, and the less synchronous UEs activation is, the more is the collision probability increased. (3) Medium release by eNB, together with LBT for UEs in the UL, leads to an even more dramatic increase in the burst resolution time. E.g., for $n = 20$ Wi-Fi stations, and a short medium release by eNB for 68μs, the resolution time increases sevenfold from 25s to 175s.

A. Model Applications

The results of our model and performance evaluation can be used for dimensioning of the networks in multiple ways. For instance, M2M application running over the sLTE-U network might have fixed requirements for the re-connection delay ("booting time"). In that case, our model can be used to determine the number of PRACH resources (preambles) per TXOP necessary to fulfill a given re-connection delay requirement. In Fig. 7, we show the delay vs. M dependency for an exemplary requirement of $T'_{\text{BR}} = 20$ s. We observe that for $n < 5$ Wi-Fi stations, $M = 5$ preambles per TXOP are sufficient, while $M \approx 40$ preambles are necessary to keep $T_{\text{BR}} < T'_{\text{BR}}$ for $n = 25$. Another possible application, in a case of a controlled environment (e.g., industrial site, intra-aircraft [3]), where Wi-Fi and LTE networks are operated together, our model can help answer the question of how many additional Wi-Fi stations can be added to an existing system without violating burst resolution time requirements.

B. Future Work

As our results in Sec. IV point out, resolution of a burst of connection requests can take unacceptably large time, especially if the eNB releases the medium prior to uplink, and UE has to perform LBT. This problem has to be addressed by the future work, and the means for decreasing connection delay ought to be developed. For example, it could be techniques for more aggressive medium access of eNB, triggered in a case of high RACH load. Additionally, presented framework could be extended to evaluate the set-up more thoroughly by relaxing a number of assumptions we made. For example, saturation assumption could be relaxed and the impact of Wi-Fi traffic load can be considered.

References

[1] ICT-317669 METIS, "Deliverable 6.6 Version 1 Final report on the METIS 5G system concept and technology roadmap," Tech. Rep., 2015.

[2] MulteFire, "MulteFire Release 1.0 Technical Paper: A New Way to Wireless," Tech. Rep., 2017.

[3] H. M. Gürsu, M. Vilgelm, W. Kellerer, and M. Reisslein, "Hybrid Collision Avoidance-Tree Resolution for M2M Random Access," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 53, no. 4, pp. 1974 – 1987, 2017.

[4] A. Laya, L. Alonso, and J. Alonso-Zarate, "Is the Random Access Channel of LTE and LTE-A Suitable for M2M Communications? A Survey of Alternatives," *IEEE Communications Surveys & Tutorials*, vol. 16, 2014.

[5] B. Chen, J. Chen, Y. Gao, and J. Zhang, "Coexistence of LTE-LAA and Wi-Fi on 5 GHz with Corresponding Deployment Scenarios: A Survey," *IEEE Communications Surveys Tutorials*, vol. 19, no. 1, pp. 7–32, 2016.

[6] 3GPP, *TR 36.889 V13 Study on Licensed-Assisted Access to Unlicensed Spectrum*, 2015.

[7] ——, *TR 37.868 V11 Study on RAN Improvements for Machine-type Communications*, 2011.

[8] S. Duan, V. Shah-Mansouri, Z. Wang, and V. Wong, "D-ACB: Adaptive Congestion Control Algorithm for Bursty M2M Traffic in LTE Networks," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 12, pp. 9847–9861, 2016.

[9] M. Vilgelm, H. M. Gürsu, W. Kellerer, and M. Reisslein, "LATMAPA: Load-Adaptive Throughput- MAximizing Preamble Allocation for Prioritization in 5G Random Access," *IEEE Access*, vol. 5, pp. 1103–1116, 2017.

[10] A. Bhorkar, C. Ibars, A. Papathanassiou, and P. Zong, "Medium access design for LTE in unlicensed band," in *Proc. IEEE Wireless Communications and Networking Conf. Workshops (WCNCW)*, Mar. 2015.

[11] ETSI, *EN 301 893 V1.8.1*, 2015.

[12] C. Chen, R. Ratasuk, and A. Ghosh, "Downlink performance analysis of LTE and WiFi coexistence in unlicensed bands with a simple listen-before-talk scheme," in *Proc. IEEE 81st Vehicular Technology Conf. (VTC Spring)*, May 2015, pp. 1–5.

[13] F. Hao, C. Yongyu, H. Li, J. Zhang, and W. Quan, "Contention window size adaptation algorithm for LAA-LTE in unlicensed band," in *Wireless Communication Systems (ISWCS), 2016 International Symposium on*. IEEE, 2016, pp. 476–480.

[14] Y. Song, K. W. Sung, and Y. Han, "Coexistence of Wi-Fi and cellular with Listen-Before-Talk in unlicensed spectrum," *IEEE Communications Letters*, vol. 20, no. 1, pp. 161–164, 2016.

[15] Z. Guan and T. Melodia, "CU-LTE: Spectrally-efficient and fair coexistence between LTE and Wi-Fi in unlicensed bands," in *Computer Communications (INFOCOM), IEEE International Conference on*. IEEE, 2016, pp. 1–9.

[16] "IEEE Standard for Information technology–Telecommunications and Information exchange between systems–Local and metropolitan area networks–Specific requirements–Part 11: Wireless LAN MAC and PHY Specifications–Amendment 4: Enhancements for Very High Throughput for Operation in Bands below 6 GHz." *IEEE Std 802.11ac-2013*, pp. 1–425, Dec. 2013.

[17] X. Wang, S. Mao, and M. X. Gong, "A survey of LTE Wi-Fi coexistence in unlicensed bands," *GetMobile: Mobile Computing and Communications*, vol. 20, no. 3, pp. 17–23, 2017.

[18] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535–547, 2000.

[19] C.-H. Wei, G. Bianchi, and R.-G. Cheng, "Modeling and analysis of random access channels with bursty arrivals in OFDMA wireless networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 4, pp. 1940–1953, 2015.

[20] J. Xu, Y. Sun, Y. Ji, and Y. Tian, "A Time and Frequency Division Algorithm for Control Signaling Collision Avoidance in Standalone LTE-unlicensed Networks," in *Proc. Int. Conf. Networking and Network Applications (NaNA)*, Jul. 2016, pp. 12–16.

[21] A. Varga, "The OMNeT++ discrete event simulation system," in *Proc. of the European Simulation Multiconference (ESM'2001)*, vol. 9, 2001.

[22] E. Jones, T. Oliphant, P. Peterson *et al.*, "SciPy: Open source scientific tools for Python," 2001, [Online; accessed 2017-03-16]. [Online]. Available: http://www.scipy.org/