This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LCOMM.2016.2557320, IEEE Communications Letters

Maximising LTE Capacity in Unlicensed Bands (LTE-U/LAA) while Fairly Coexisting with 802.11 WLANs

Víctor Valls, Andrés Garcia-Saavedra, Xavier Costa and Douglas J. Leith

***Abstract*—We propose a channel access mechanism that allows LTE to operate in the 5 GHz unlicensed band (LTE-U/LAA) and fairly coexist with 802.11 WLANs. The proposed mechanism is compliant with Listen Before Talk (LBT), and it can be configured to maximise the channel time used by LTE-U stations while fairly coexisting with 802.11 WLANs. That is, an LTE-U station will not affect the throughput of a WLAN more than if it were an 802.11 station.**

***Index Terms*—WLAN, 802.11, LTE-U, LAA, coexistence, fairness, listen before talk, LBT.**

I. INTRODUCTION

WIRELESS communications have shifted from bit rates of a few Mb/s to Gb/s in order to cope with the increasing demand for bandwidth during the last ten years. This increase in data rates has been achieved by means of using higher modulation schemes, improved channel codes, MIMO transmissions, *etc*. Nevertheless, the use of more spectrum remains still the most effective and simple way to increase network throughput.

In the case of cellular networks, operators have started to use unlicensed bands as a means of decongesting the scarce and expensive licensed spectrum. For instance, 3GPP Rel. 12 allows mobile devices to offload traffic to an IEEE 802.11 network. Currently, the 3GPP is considering to use LTE in the 5 GHz unlicensed band (LTE-U/LAA) for the upcoming version of LTE Rel. 13; however, the benefits of using LTE-U rather than a hybrid solution of LTE + IEEE 802.11 are the subject of ongoing discussion within the community. On the one hand, it seems clear that LTE-U has the advantages of (i) seamless integration with the legacy mobile system architecture, and (ii) simpler co-ordination across transmitters to, for example, leverage signal cancellation techniques. On the other hand, LTE-U is forced to implement channel access coexistence mechanisms that may impact on the achievable throughput gain (compared to a hybrid solution) and on 802.11 stations. As a result, the benefits of using LTE in the unlicensed band remain still unclear.

In this paper we propose a coexistence mechanism that allows LTE to fairly coexist with WLANs, while achieving a higher throughput than if it were an 802.11 station. The proposed mechanism divides the total channel airtime into two orthogonal airtimes, and allows an LTE-U station to maximise its allocated airtime without degrading the throughput of a WLAN more than what an 802.11 station would. Further, the proposed mechanism is compliant with the Listen Before Talk (LBT) technique specified in ETSI 301 893 [1] for the 5 GHz unlicensed band, which eases deployability.

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II. RELATED WORK

The requirement for coexistence with 802.11 WLANs is not new and has already been studied for Bluetooth, Zigbee and WiMaX. The work in [2] shows that without a coexistence mechanism LTE can significantly affect the performance of a WLAN. In [3] the authors propose a modified version of Almost Blank Subframes (ABS) that does not include reference signals, *i.e.*, the LTE remains silent in order to allow 802.11 stations to attempt to transmit. The work in [4] and [5] propose, respectively, coexistence mechanisms based on duty-cycle and LBT while providing fairness. However, the throughput benefit (if any) of using LTE-U rather than a LTE + IEEE 802.11 solution is not clear. A range of LBT-compliant mechanisms and respective evaluations are presented in the 3GPP's LTE-U coexistence study [6]. They show that in some scenarios an LTE-U station can be configured to not degrade the performance a WLAN more than if another 802.11 station were added to the WLAN. Nevertheless, the configurations are implementation-dependent and some of the parameters values needed are unlikely to be known in real networks. Also, none of them quantify the airtime or throughput gain compared to using a hybrid solution.

III. COEXISTENCE MECHANISM DESIGN

A. Preliminaries

We start reviewing two aspects that are fundamental for the design of a coexistence mechanism with 802.11 WLANs: (i) regulatory constraints, and (ii) the Distributed Coordinated Function (DCF) in IEEE 802.11. Regarding regulation, in this work we focus on the European regulation, ETSI 301 893 [1], because it is the most restrictive and a solution compliant with it is therefore widely deployable. Further, in order to stress that the coexistence mechanism we consider here extends to any technology that seeks to operate in the 5 GHz band, we will refer to an LTE-U station as an LBT-station for the rest of the paper.

1) Listen Before Talk: ETSI 301 893 [1] specifies that before a transmission a station must perform a Clear Channel Assessment (CCA) using energy detection for at least 20 µs. Namely, depending on the energy detected during a time equal to or greater than 20 µs (see [1] for a detailed description of the thresholds) the channel is declared *idle* or *busy*. In case the channel is declared *idle* the station can start a transmission immediately, otherwise it needs to perform another CCA.

When to perform another CCA after the channel is declared *busy* depends on the LBT operation mode, which can be Frame Based Equipment (FBE) or Load Based Equipment (LBE) – both specified in [1]. In the coexistence mechanism we propose here (Section III-B) an LBT-station will always sense the channel *idle* and so FBE and LBE will be equivalent in terms of channel access. FBE and LBE also specify parameters (*e.g.*, maximum transmission time) that need to be considered in order to be fully compliant with the regulation.

2) IEEE 802.11 MAC protocol: A detailed description of the IEEE 802.11 DCF with Binary Exponential Backoff (BEB) can be found in [7]. However, we include a brief description for completeness. An IEEE 802.11 network divides time into MAC slots and a station transmits after observing Y_m idle slots, where Y_m is a random variable selected uniformly at random from $\{0, 1, \dots, 2^m CW_{\text{min}} - 1\}$ where $CW_{\text{min}} \in \mathbb{N}$ is the minimum contention window and $m = 0, 1, 2, \dots$ is the number of successive collisions experienced by the station. After a successful transmission m is set to 0. IEEE 802.11 defines a parameter CW_{max} that limits the expected number of idle slots a station has to wait after m successive collisions, *i.e.*, $2^m CW_{\text{min}} = CW_{\text{max}}$ for $m \geq \bar{m}$.

Important characteristics of IEEE 802.11 WLANs relevant for this work are: (i) 802.11 includes in the packet the duration of a transmission, *i.e.*, upon correct reception of a packet header an 802.11 station knows the duration for which the channel will be busy; (ii) in IEEE 802.11 EDCA MAC, after a successful transmission all stations in the WLAN wait for an Arbitration Inter-Frame Spacing (AIFS) time of at least 34 µs[1]. That is, after each successful transmission there will be at least 34 µs where the channel will be free of 802.11 transmissions.

B. Orthogonal Airtime Coexistence

Our coexistence mechanism builds on the key observation that the minimum duration of an AIFS (34 µs) is longer than the CCA minimum time (20 µs) specified in the regulation. Hence, if an LBT-station performs a CCA at the beginning of an AIFS period, the channel will be sensed idle and the LBT-station (with FBE or LBE) will transmit before any 802.11 station does. Note that the latter will always be true if there is no interference that makes the LBT-station sense the channel busy, which we will assume is the case. Also, note that an LBT-station can discover when an AIFS period starts by listening to the channel using an IEEE 802.11 interface – this is common practice in coexistence, see [4] for example.

In short, the channel access part in the proposed coexistence mechanism consists of two parts:

1) An LBT-station performs a CCA only at the beginning of an AIFS period.
2) At the start of each transmission an LBT-station sends (using the 802.11 interface) a CTS-to-self[2] indicating the time the channel will be occupied.

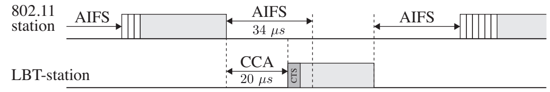

Fig. 1: Schematic illustration of the channel access used by an LBT-station in the coexistence mechanism. An LBT-station can sense the channel free for 20 µs after each 802.11 successful transmission, and transmit before any other 802.11 stations does.

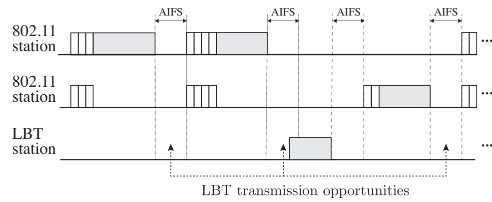

Fig. 2: Illustrating the transmission opportunities of an LBT-station in a WLAN with two 802.11 stations. The LBT-station controls its transmission attempt rate in order to comply with our coexistence criterion. In this example the LBT-station transmits only in the second transmission opportunity.

The first point ensures that the channel is always sensed idle, and the second point that the 802.11 stations do not transmit while the LBT-station is transmitting. Note that since the channel is always sensed *idle* the policies specified in FBE and LBE as to how to perform another CCA when the channel is sensed *busy* are irrelevant for this work. The channel access mechanism is schematically illustrated in Figure 1 for a network with one 802.11 station and one LBT-station. Observe from the figure that the LBT-station is able to transmit before the 802.11 station does, and that the next AIFS period starts when the LBT-station has finished its transmission.

An important characteristic of the proposed coexistence mechanism is that under our assumptions an LBT-station will never collide with an 802.11 station. Hence, an LBT-station does not affect the transmission attempt probability of the stations in a WLAN, and therefore, the airtime in the system is divided into two *orthogonal* airtimes. Note, however, that collisions amongst LBT-stations can happen. Because of this, in the rest of the paper we will assume for simplicity that there is a single LBT-station in the network. This assumption is in line with the 3GPP and work in the literature, and corresponds to the case where there is a single LTE-U station carrying out downlink offloading, and cellular operators use different channels in order to do not interfere with each other. In Section V we will briefly discuss how to allow multiple LBT-stations in the network. Note as well that the proposed channel access needs of 802.11 transmissions in order to work; however, it is reasonable to assume that when there are not "sufficient" 802.11 transmissions there is no coexistence issue.

So far we have specified how an LBT-station should access the channel, but not how much airtime it can use in order to be compliant with our coexistence criterion: do not degrade the throughput of a WLAN more than what another 802.11 station would.[3] Airtime usage can be adjusted by controlling the probability with which an LBT-station (see example in

[1]The AIFS value depends on the version of the 802.11 amendment implemented, the packet's Access Category (AC) and the vendor's configuration of the access point (AP). The AIFS time corresponds to the DCF Inter-Frame Space (DIFS) in DCF-based devices, and in the 5 GHz bands it has a duration of at least 34 µs.

[2]The mechanism used by APs to prevent a transmission from being interrupted.

[3]We leave the study of the impact on the delay for future work, however, we believe that the impact on the delay would be mild when the LTE-U's and 802.11's transmission times are similar.

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Figure 2). The rest of the paper is devoted to finding the transmission attempt probability of an LBT-station that maximises its airtime and satisfies our coexistence criterion.

IV. Coexistence Airtime

A. Network Setup

Consider a WLAN with ideal channel conditions *i.e.*, no hidden nodes and capture effect) and n saturated stations, *i.e.*, each station has always a packet ready for transmission. It is well known that under these conditions the conditional transmission attempt probability of a station in a MAC slot – which depends on the number of stations and the BEB configuration – can be modelled as the probability of transmitting in each MAC slot with a fixed probability [8]. That is, a station $i \in \{1, \dots, n\}$ transmits in a MAC slot with probability $\tau_i^{(n)} \in [0, 2/(CW_{\text{min}}+1)]$. We will assume that the 802.11 stations are homogeneous and therefore $\tau^{(n)} = \tau_i^{(n)}$ for all $i \in \{1, \dots, n\}$. Then, the probability that a MAC slot is idle is given by the probability that none of the stations transmit, $P_{\text{idle}}^{(n)} = (1-\tau^{(n)})^n$; the probability that it is occupied by a successful transmission is $P_{\text{succ}}^{(n)} = np_{\text{succ}}^{(n)}$, where $p_{\text{succ}}^{(n)} = \tau^{(n)}(1-\tau^{(n)})^{n-1}$ is the probability that a single station transmits in a MAC slot. Finally, the probability that a slot is occupied by a collision is given by $P_{\text{coll}}^{(n)} = 1 - P_{\text{idle}}^{(n)} - P_{\text{succ}}^{(n)}$ and the probability of a slot being busy is $P_{\text{tx}}^{(n)} = P_{\text{coll}}^{(n)} + P_{\text{succ}}^{(n)}$. The throughput of an 802.11 station is given by

$$s^{(n)} = \frac{p_{\text{succ}}^{(n)} B}{P_{\text{idle}}^{(n)}\sigma + (1-P_{\text{idle}}^{(n)})T}, \tag{1}$$

where σ, B and T are, respectively, the duration of a MAC slot, the expected number of bits in a transmission, and the duration of a transmission (successful or collision), which we assume it is constant.

B. Maximising Airtime

We aim to obtain the maximum fraction of orthogonal airtime that an LBT-station can use such that the average throughput experienced by an 802.11 station is not degraded more than if another 802.11 station were added to the network. Since LBT transmissions are orthogonal to 802.11 transmissions, an LBT-station can be regarded (in terms of airtime) as an 802.11 station that transmits in MAC slots that otherwise would be idle. Then, the LBT airtime can be expressed as

$$A_{\text{LBT}} = \rho P_{\text{idle}}^{(n)}(T' - \sigma) \tag{2}$$

where $\rho \in [0,1]$ is the fraction of idle slots that would change to busy slots, and $(T'-\sigma) := T_{\text{LBT}} > 0$ is the duration of an LBT-station's transmission which depends on the LBT mode used (FBE or LBE). Note that quantity $\rho P_{\text{idle}}^{(n)}$ is the fraction of orthogonal LBT transmissions. With (2) we can write the throughput experienced by an 802.11 station when a LBT-station uses A_{LBT} airtime as follows

$$s^{(n+\text{LBT})} := \frac{p_{\text{succ}}^{(n)} B}{P_{\text{idle}}^{(n)}\sigma + P_{\text{tx}}^{(n)}T + \rho P_{\text{idle}}^{(n)}(T'-\sigma)}. \tag{3}$$

Next, since the throughput of a station in a WLAN is non-increasing with the number of stations, *i.e.*, $s^{(n)} \geq s^{(n+1)}$ for every $n = 1, 2, \dots$ we have that

$$s^{(n+1)} = \frac{p_{\text{succ}}^{(n+1)} B}{P_{\text{idle}}^{(n+1)}\sigma + P_{\text{tx}}^{(n+1)}T} \leq s^{(n+\text{LBT})} \tag{4}$$

will always hold provided ρ in (3) is sufficiently small. We are interested in finding the value of ρ that makes (4) tight, *i.e.*, maximises the LBT airtime. We have the following lemma.

Lemma 1. *Consider a WLAN with n homogeneous stations in saturated conditions. Suppose $T, T' > \sigma$. Then, (4) holds for every $\rho \in [0, \bar{\rho}]$ with*

$$\bar{\rho} := \min\left\{1, \left(\frac{T-\sigma}{T'-\sigma}\right)\min\left\{1, \frac{P_{tx}^{(n+1)}}{p_{succ}^{(n+1)}}\frac{p_{succ}^{(n)}}{P_{idle}^{(n)}} - \frac{P_{tx}^{(n)}}{P_{idle}^{(n)}}\right\}\right\} \tag{5}$$

Proof: Rearranging terms in (4) with $P_{\text{tx}} = (1 - P_{\text{idle}})$ and $A = \rho P_{\text{idle}}^{(n)}(T'-\sigma)$ we have that

$$\frac{p_{\text{succ}}^{(n)}}{p_{\text{succ}}^{(n+1)}} \geq \frac{P_{\text{idle}}^{(n)}(\sigma - T) + T + \rho P_{\text{idle}}^{(n)}(T'-\sigma)}{P_{\text{idle}}^{(n+1)}(\sigma - T) + T}. \tag{6}$$

Further rearranging we obtain that

$$\begin{aligned}
&\rho P_{\text{idle}}^{(n)}(T'-\sigma) \\
&\leq \frac{p_{\text{succ}}^{(n)}}{p_{\text{succ}}^{(n+1)}}(P_{\text{idle}}^{(n+1)}(\sigma - T) + T) - P_{\text{idle}}^{(n)}(\sigma - T) - T, \\
&= T\left(\frac{p_{\text{succ}}^{(n)}}{p_{\text{succ}}^{(n+1)}} - 1\right) + \left(P_{\text{idle}}^{(n)} - \frac{p_{\text{succ}}^{(n)}}{p_{\text{succ}}^{(n+1)}}P_{\text{idle}}^{(n+1)}\right)(T-\sigma),
\end{aligned}$$

and dividing by $P_{\text{idle}}^{(n)}(T'-\sigma)$ yields

$$\rho \leq \frac{T}{P_{\text{idle}}^{(n)}(T'-\sigma)}\left(\frac{p_{\text{succ}}^{(n)}}{p_{\text{succ}}^{(n+1)}} - 1\right) + \left(1 - \frac{p_{\text{succ}}^{(n)}}{p_{\text{succ}}^{(n+1)}}\frac{P_{\text{idle}}^{(n+1)}}{P_{\text{idle}}^{(n)}}\right).$$

Now fix $T' = T$ and see that since $T/(T-\sigma) > 1$ we have

$$\begin{aligned}
\rho &\leq \frac{1}{P_{\text{idle}}^{(n)}}\left(\frac{p_{\text{succ}}^{(n)}}{p_{\text{succ}}^{(n+1)}} - 1 + P_{\text{idle}}^{(n)} - \frac{p_{\text{succ}}^{(n)}}{p_{\text{succ}}^{(n+1)}}P_{\text{idle}}^{(n+1)}\right), \\
&\leq \min\left\{1, \frac{P_{\text{tx}}^{(n+1)}}{p_{\text{succ}}^{(n+1)}}\frac{p_{\text{succ}}^{(n)}}{P_{\text{idle}}^{(n)}} - \frac{P_{\text{tx}}^{(n)}}{P_{\text{idle}}^{(n)}}\right\}, \qquad (7)
\end{aligned}$$

where in (7) we have used the fact that $1 - P_{\text{idle}} = P_{\text{tx}}$ and $\rho \leq 1$. Finally, when $T' \neq T$, since all it matters is the total airtime A_{LBT} given in (2), if we multiply (7) by $(\frac{T-\sigma}{T'-\sigma})$ the stated result follows. ■

With Lemma 1 we can obtain the fraction of orthogonal/successful LBT transmissions ($\rho P_{\text{idle}}^{(n)}$) of expected duration $T_{\text{LBT}} = T' - \sigma$ that can be accommodated in order to be compliant with our coexistence criterion. Importantly, the bound in (5) depends on $P_{\text{tx}}^{(n+1)}$ and $p_{\text{succ}}^{(n+1)}$, however, in saturation conditions a very good approximation of these values can be easily obtained [7].

We can easily map the fraction of orthogonal LBT transmissions to the probability of transmitting during an AIFS period. Observe we can write $P_{\text{idle}}^{(n)}\sigma + P_{\text{tx}}^{(n)}T + \rho P_{\text{idle}}^{(n)}(T'-\sigma) =$

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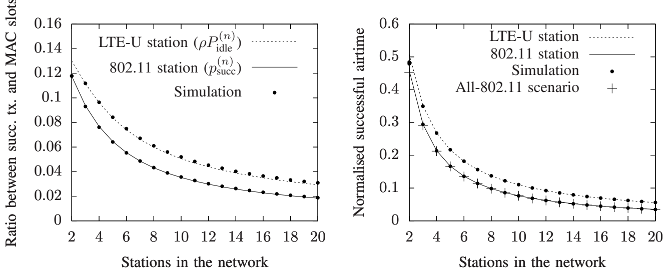

(a) (b)

Fig. 3: Illustrating the (a) ratio between successful transmissions and MAC slots; (b) stations' successful airtime, in a network with a single LTE-U station (LBT-station) and $\rho = \bar{\rho}$. Network parameters are $T = 100\sigma$, $T' = T_{\text{LBT}} + \sigma$, $T_{\text{LBT}} = T$, $CW_{\text{min}} = 16$ and $\bar{m} = 5$.

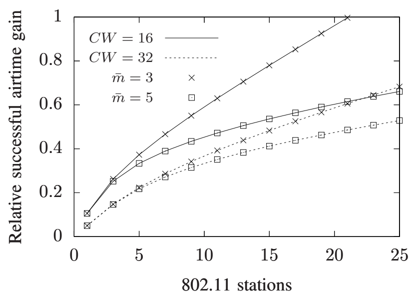

Fig. 4: Illustrating the relative successful airtime gain of an LTE-U station (with $\rho = \bar{\rho}$) compared to an 802.11 station.

$P_{\text{idle}}^{(n)}\sigma + (P_{\text{succ}}^{(n)} + P_{\text{coll}}^{(n)})T + \rho P_{\text{idle}}^{(n)} T_{\text{LBT}} = P_{\text{idle}}^{(n)}\sigma + (P_{\text{succ}}^{(n)} + \rho P_{\text{idle}}^{(n)} \frac{T_{\text{LBT}}}{T})T + P_{\text{coll}}^{(n)} T = P_{\text{idle}}^{(n)}\sigma + (P_{\text{succ}}^{(n)} + \pi)T + P_{\text{coll}}^{(n)} T$ where

$$\pi := \rho P_{\text{idle}}^{(n)} (T_{\text{LBT}}/T). \tag{8}$$

That is, if an LBT-station attempts to transmit after a successful 802.11 transmission with probability (8) and $\rho \in [0, \bar{\rho}]$, it will be compliant with our coexistence criterion.

Figure 3a shows the ratio between successful transmissions and MAC slots in a network with a single LTE-U station (LBT-station) with $\rho = \bar{\rho}$ and parameters $T = 100\sigma$, $CW_{\text{min}} = 16$, $\bar{m} = 5$, $T' = T_{\text{LBT}} + \sigma$ and $T_{\text{LBT}} = T$. Observe from the figure that the LTE-U station has always a larger fraction of successful transmissions, and since $T = T_{\text{LBT}}$, the LTE-U station will obtain a larger amount of (successful) airtime than an 802.11 station. The latter can be verified in Figure 3b, where the normalised successful airtime of the LTE-U station and 802.11 station is shown. Importantly, see from the figure that the successful airtime of an 802.11 station is not less than the airtime it would have had if the LTE-U station were an 802.11 station, *i.e.*, all stations in the network were 802.11. Figure 4 shows the relative successful airtime gains of an LTE-U station compared to an 802.11 station for a range of network parameters. Observe from the figure that the gains are larger with smaller CW and $\bar{m}$, and increase with the number of 802.11 station in the WLAN.

V. Practical Considerations and Discussion

To conclude the paper we discuss some points that must be considered when implementing the coexistence mechanism.

1) *Multiple LBT-stations*: In this case collisions between LBT-stations can happen, and LBT-stations need to use a channel access coordination mechanism in order to mitigate the impact of collisions. This can be achieved, for example, in a centralised manner or by implementing a DCF-like scheme to transmit in the AIFS periods. In the case of LTE-U a centralised approach makes sense since the licensed band can be used as a means to exchange coordination information.

2) *Non-saturated stations:* Since the LBT and 802.11 airtimes are orthogonal, an LBT-station affects a non-saturated 802.11 station either by (i) leaving it non-saturated or (ii) saturating it. If the 802.11 station does not get saturated coexistence is irrelevant because all traffic can be served; and if the 802.11 station gets saturated we can then compute the optimal airtime in order to be compliant with our coexistence criterion. The key part here is that since an LBT-station does not collide with the 802.11 stations in a WLAN, it is possible to analyse the traffic in the network to determine the number of contending stations [8]. Further, under regularity conditions it is possible to determine how many stations are actually saturated.

3) *LTE-U/LAA overheads:* LTE-U has specific transmission requirements that will affect the total airtime used to transmit data, *i.e.*, the throughput. A simple way to reduce the LTE-U/LAA overheads would be to increase the duration of transmissions, however, this will come at the price of increasing the delay for both 802.11 and LTE-U stations. The minimisation of the LTE-U/LAA overheads while keeping a low delay is an interesting subject of research in future work.

VI. Conclusions

We have proposed a coexistence mechanism that allows LTE to operate in unlicensed bands and that is compliant with the Listen Before Talk (LBT) technique specified in ETSI 301 893. The proposed mechanism can be configured to maximise LTE-U's airtime while not degrading the throughput of an 802.11 station more than what another 802.11 station would. The main benefit of the proposed solution is a significant relative airtime gain for LTE-U systems which increases as the number of competing 802.11 stations grows (*e.g.*, $>50\%$ for 25 stations in the considered scenario).

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