Energy-efficient LTE/Wi-Fi Coexistence

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***Abstract*—Motivated by the shared spectrum paradigm, we address the problem of implicit coordination between coexisting wireless systems that do not share a common control plane. We consider the coexistence of LTE and Wi-Fi and study mechanisms for conserving energy when the wireless channel is occupied. In a Wi-Fi only system, the network allocation vector (NAV) included in the header of IEEE 802.11 frames advertises the duration of an imminent transmission. Nearby Wi-Fi terminals decode the frame header and transition to sleep mode to conserve energy. However, when heterogeneous systems coexist (e.g., LTE and Wi-Fi), frames that belong to other systems are not decodable. This leads to continuous channel sensing even when the channel is to be occupied for a long duration. We design two implicit mechanisms to play the role of the NAV. Our mechanisms predict the duration of an imminent LTE transmission by predicting the frame's traffic class. The prediction is based on the elapsed idle slots between successive transmissions and the transmission history. We show that our methods achieve significant energy savings without stifling transmission opportunities.**

I. Introduction

The ever-increasing demand for wireless services has led to an exponential increase in mobile data traffic and a severe shortage in radio spectrum resources. One promising approach to address the spectrum scarcity is to allow the offloading of network traffic to unlicensed bands, leading to the coexistence of heterogeneous wireless systems [1], [2]. As an example, the long term evolution (LTE) unlicensed standards regulate the coexistence of LTE stations with Wi-Fi terminals in the 5GHz unlicensed band. The LTE-U standard implements a duty cycle approach [1], whereas the LTE-LAA standard implements a Listen-Before-Talk (LBT) mechanism that coordinates channel access based on channel sensing [3]. The latter has been favored in recent standard releases, e.g. LTE release 15 [3], as it allows fairer spectrum allocation.

The main challenge is achieving a fair and efficient coexistence without a common control plane. For instance, consider the coexistence of two LTE stations A and B with three Wi-Fi terminals C, D, and E, as shown in Fig. 1. Let C capture the channel first. The Wi-Fi terminal C defers for a backoff time, followed by a data transmission and an ACK response from D. The frame header contains a network allocation vector (NAV) field that advertises the duration of the Wi-Fi transmission. All neighboring Wi-Fi terminals decode the header to determine the frame destination. If a terminal is not the destination,

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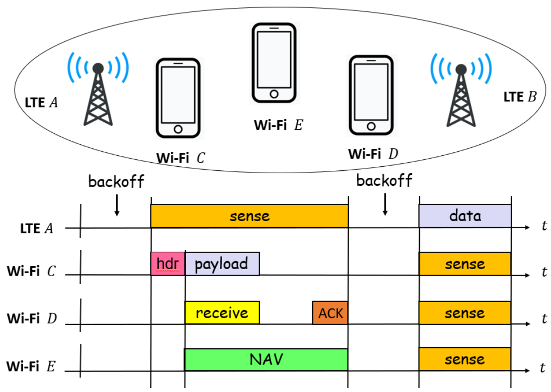


Fig. 1: LAA-LTE/Wi-Fi Coexistence.

it uses the NAV to switch its receiver to a sleep state and conserve energy.

However, when LTE station A is transmitting to B, the coexisting Wi-Fi stations cannot decode the LTE frame. As a result, they have no way to determine the duration of the LTE transmission. Instead, they continuously sense the channel to be able to contend once the channel is freed. The same phenomenon occurs when the LTE station overhears a Wi-Fi transmission, as it has no way to determine its duration. The energy consumption during this idle sensing state is several orders of magnitude higher than that in a sleep state [4]. *We study the problem of predicting the transmission duration of LTE stations at the beginning of each transmission, with the purpose of setting the Wi-Fi receiver to sleep mode*. A requirement is that the prediction is performed implicitly, without decoding LTE transmissions or signaling.

Contributions: Our contributions are summarized as follows:

- We develop an implicit technique that enables Wi-Fi terminals estimate the duration of LTE transmissions. We exploit the unique backoff characteristics of each LTE priority class to predict the length of an imminent LTE transmission.
- We propose two class estimation mechanisms. The first is a conservative mechanism that maximizes the Wi-Fi sleep time without missing any opportunity to contend for the channel. In the second mechanism, we apply Bayesian estimation to get a more accurate prediction of the priority class and avoid waking up the receiver too early. This comes at the expense of oversleeping when a high priority class is misclassified, thus leading to a small loss in transmission opportunities.

- Our simulations show that the first approach reduces energy consumption by at least 60% with zero oversleeping probability, whereas the second approach conserves up to 85% energy, at the expense of at most 4 % loss in transmission opportunities.

Although we present our work from the Wi-Fi perspective, the same methodology can be applied at the LTE side.

II. Background and Related Work

A. Wi-Fi Power Management

In the IEEE 802.11 family of standards [5], a Wi-Fi terminal supports several power management modes. Each mode is a combination of device activity and network connectivity. The power-management modes when the terminal is in the connected state are described below.

1) Active: the Wi-Fi terminal is connected to the network and is actively transmitting or receiving.
2) Idle: the Wi-Fi terminal is connected to the network but is not actively transmitting or receiving.
3) Sleep: the Wi-Fi terminal is connected to the network, but the remainder of the platform is in a low-power state.

Wi-Fi terminal transitions between these modes at different stages of the 802.11 protocol. When it is involved in a transmission/reception, the terminal is in active mode. If it is monitoring the channel for a transmission opportunity (e.g., during the backoff period), the terminal is in idle mode, whereas it transitions to sleep mode for the period of time when other terminals are active. The power consumption is about 1.687W while transmitting and 1.585W while receiving. The consumption drops to 1.038W in idle mode, and only 0.088W in sleep mode [4]. It is evident that setting the terminal to sleep mode, when possible, can lead to dramatic energy savings.

B. LAA-LTE Release 15

The LAA-LTE standard, as specified in the 3GPP Release 15 [3], defines the four traffic priority classes shown in Table I. Each class C_ℓ is defined by a three-tuple $(\rho_\ell, T_\ell^{MCOP}, \mathbf{q}_\ell)$ where ρ_ℓ is the number of observation slots, T_ℓ^{MCOP} is the maximum channel occupancy time, and $\mathbf{q}_\ell$ is the set of contention window sizes. The channel access mechanism of LAA-LTE is illustrated in Fig. 2 and involves these steps:

1) Upon the end of a transmission, an LTE station senses the channel for T_{init}, which consists of a defer time $T_{def} = 16\mu s$ plus ρ_ℓ observation slots of $T_s = 9\mu s$ each. If the channel stays idle during T_{init}, the LTE station initiates the backoff process. Otherwise, the channel sensing is repeated.
2) During the backoff stage, the LTE station uniformly draws a backoff counter B_ℓ from $[0, q_{\min} - 1]$. The LTE station decrements its backoff counter by one with every idle slot and freezes it on a busy slot. The backoff countdown resumes if the channel is idle for T_{init}.
3) When $B_\ell = 0$, the LTE station transmits a frame with a maximum duration of T_ℓ^{MCOP} and waits for the ACK. If the ACK is received before a timeout, this transmission round is completed, Otherwise, the process is repeated with a doubled CW.

Fig. 2: Backoff between two consecutive transmissions.

TABLE I: Priority Classes in LTE-LAA.

Priority Class	ρ_ℓ	$q_{\ell_{\min}}$	T_ℓ^{MCOP} (ms)	Allowed $\mathbf{q}_\ell$ sizes
C_1	1	4	2	$\{4, 8\}$
C_2	1	8	3	$\{8, 16\}$
C_3	3	16	8 or 10	$\{16, 32, 64\}$
C_4	7	16	8 or 10	$\{16, 32, \ldots, 1024\}$

C. Related work

The LTE/Wi-Fi coexistence in unlicensed bands has created new challenges for fair and efficient resource management [6]–[8]. Several studies have shown a performance degradation in both systems due to the absence of a common control plane (e.g., [6]). To tackle this problem, recent works have developed implicit methods to estimate the operational parameters of heterogeneous systems that do not require frame decoding [7], [9]. However, the energy efficiency under LTE/Wi-Fi coexistence has not been explored at length. In [10], the authors investigated the reduction of power consumption by applying downlink power control for LTE-U.

Energy-efficient medium access has been a topic of extensive research in homogeneous wireless networks. Since early standardization efforts, the 802.11 family of protocols includes a power saving mode (PSM) that allows devices to sleep when the channel is idle for long periods [5]. A periodic wake up function is used to listen for incoming packets. A similar approach has been studied for wireless sensor networks (WSN) [11]–[13]. Ingram *et al.* proposed a cooperative duty cycle MAC protocol that enables nodes to save energy by transitioning to sleep state in idle listening periods [11]. Dam *et al.* proposed T-MAC, a dynamic duty cycle protocol that reduces energy consumption by dynamically ending the active duty cycle [12]. The duty cycle-based solutions proposed for WSNs are not suitable for high traffic scenarios. Moreover, periodic wake ups are not throughput-effective under saturation conditions studied in this work.

III. System Model

We consider the coexistence of an LAA-LTE system with a set of Wi-Fi terminals in the 5GHz unlicensed band. Without loss of generality, we study the coexistence in a single collision domain under backlogged traffic conditions. The LTE stations and Wi-Fi terminals follow the LAA-LTE and IEEE 802.11ac standards, respectively. LTE stations operate on the four priority classes shown in Table I. Wi-Fi terminals are assumed to transition between active, idle, and sleep

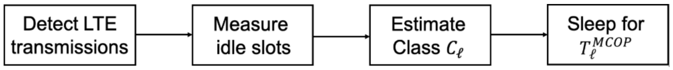


Fig. 3: Steps for transitioning to sleep mode.

modes while competing for the channel access. The power consumption of Wi-Fi terminals is denoted by P_A, P_I and P_S in active, idle, and sleep modes, respectively.

Problem statement: Consider a Wi-Fi terminal X operating over a period of time T, such that

$$T = T_A + T_I + T_S, \tag{1}$$

where T_A, T_I, and T_S are the times spent in active mode, idle mode, and sleep mode, respectively. The total energy E_T consumed by X over T is given by

$$E_T = P_A \cdot T_A + P_I \cdot T_I + P_S \cdot T_S. \tag{2}$$

Our objective is to conserve energy at X by minimizing E_T without affecting the active mode time T_A. This is the time spent in useful communications, either transmission or reception. That is, the active time T_A has to be fixed while optimizing the energy conservation. As P_I is always much greater than P_S [4], minimizing E_T becomes equivalent to maximizing T_S or minimizing T_I. We highlight that $T_I + T_S$ must be fixed to $T - T_A$, i.e., the relation between T_I and T_S is pareto-optimal. To increase one of them, you have to decrease the other by the same amount. In conclusion, our objective is to decrease the time in which the Wi-Fi terminal senses the occupied channel vainly.

IV. Proposed Power-saving Mechanisms

We propose implicit mechanisms that enable a Wi-Fi terminal recognize opportunities to conserve more energy by transitioning from idle mode to sleep mode. Ideally, the Wi-Fi terminal should be allowed to sleep during the time in which the LTE is occupying the channel. This time is expected to equal T_ℓ^{MCOP} when an LTE transmits a frame following class C_ℓ. From Table I, the duration T_ℓ^{MCOP} can be inferred by predicting the class C_ℓ of a transmitted LTE frame. However, this poses several challenges because LTE headers are undecodable by Wi-Fi terminals. We *implicitly estimate* the class of an imminent LTE transmission using protocol semantics and prior history. Our mechanisms consist of the steps shown in Fig. 3. Initially, a Wi-Fi terminal X monitors the channel and counts the elapsed idle slots between two consecutive transmissions attributed to the same LTE station. The number of idle slots is directly related to the choice of the priority class, hence it is used to estimate the class C_ℓ. However, a Wi-Fi terminal X is not necessarily able to identify C_ℓ with certainty. It is possible that more than one class lead to the same number of idle slots, as there are intersections between the corresponding contention window sizes. Thus, this estimation is performed using two approaches. The first approach is a conservative one where X selects the class with the minimum possible T_ℓ^{MCOP}. This guarantees that X will not miss a transmission opportunity by oversleeping, but can lead to higher energy consumption because X tends to wake up too early. In the second approach, we apply Bayesian estimation to accurately estimate the priority class, at the expense of a non-zero oversleeping probability. We note that both approaches require an accurate estimate of the idle slots number between consecutive LTE transmissions, which subsequently requires the ability to detect these LTE transmissions.

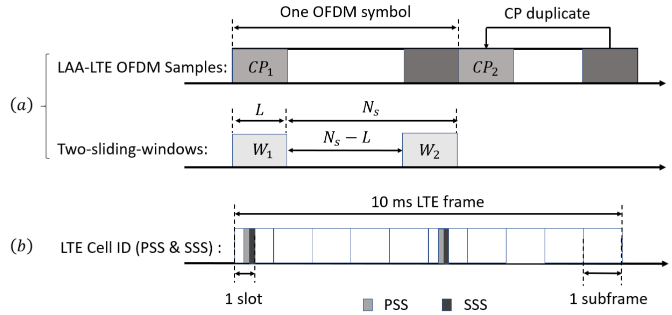


Fig. 4: Detecting LTE transmissions.

A. Detecting LTE Transmissions

In this step, a Wi-Fi terminal attributes LTE transmissions to unique LTE identities (IDs). First, the Wi-Fi identifies an LTE signal using the OFDM signal features. We employ the implicit LTE signal identification mechanism presented in [7]. The main idea is to detect the unique spacing of the cyclic prefix (CP) in OFDM LTE signals by computing the signal correlation on the samples of the received signal, as shown in Fig. 4(a). Because the CP is a replica of the end of an OFDM symbol, the signal correlation is high when the L samples corresponding to the CP are correlated with their replicas spaced at $N_s - L$ samples away, where N_s is the number of data samples. The unique LTE CP spacing reveals an LTE transmission.

We further adopt a signal-correlation based mechanism to differentiate between LTE stations as proposed in our prior work [9]. In an LTE frame header, the Primary Synchronization Signal (PSS) and Secondary Synchronization Signal (SSS) denote the unique physical layer identity of an LTE station. Each LTE frame, belonging to the same LTE station, carries the same PSS and SSS at fixed locations, as shown in Fig. 4(b). Two LTE transmissions can be attributed to the same LTE station if the signal correlation between the respective PSS and SSS fields is high. Note that both the LTE detection and LTE station differentiation are performed implicitly based on signal sampling and do not require header decoding.

B. Idle slots estimation

Consider the $(i-1)^{st}$ and i^{th} successive transmissions of an LTE station A, as shown in Fig. 5. Let ν_i be the number of intermediate transmissions that belong to other terminals. Let also T_j be the idle time (in slots) preceding the j^{th} intermediate transmission, where T_{ν_i+1} is the idle time before the i^{th} LTE transmission. Between the two successive transmissions of A, the total number of idle slots $N(i)$ can be expressed as

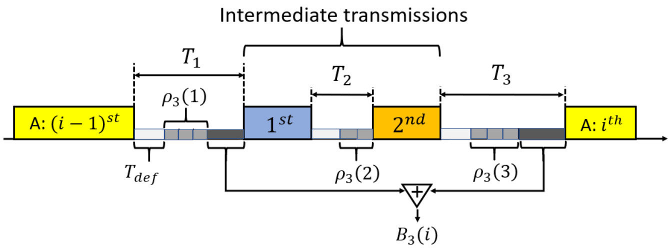


Fig. 5: Elapsed time between two successive transmissions.

$$N(i) = \sum_{j=1}^{\nu_i+1} T_j. \tag{3}$$

If the i^{th} transmitted frame belongs to class C_ℓ, then $N(i)$ can be equivalently expressed as

$$N_\ell(i) = B_\ell(i) + \sum_{j=1}^{\nu_i+1} \left(\rho_\ell(j) + T_{def}\right), \tag{4}$$

where $B_\ell(i)$ is the backoff counter selected for the i^{th} LTE transmission. The second term in (4) consists of the sum of all defer times and observation slots that are experienced by A due to the ν_i intermediate transmissions from other stations. There are two cases to correctly account for $\rho_\ell(j)$:

1) The channel stays idle until the observation slots are over, then $\rho_\ell(j) = \rho_\ell$.
2) The next intermediate transmission starts before the observation slots are exhausted. In this case, the idle time T_j includes T_{def} plus $\rho_\ell(j) < \rho_\ell$ observation slots.

Finally, for T_{ν_i+1}, the LTE always has $\rho_\ell(j) = \rho_\ell$ because the LTE captures the channel right after this idle period. For all cases, the observation slots $\rho_\ell(j)$ can be consolidated to

$$\rho_\ell(j) = \begin{cases} \min\{\rho_\ell, T_j - T_{def}\}, & 1 \le j \le \nu_i, \\ \rho_\ell, & j = \nu_i + 1. \end{cases} \tag{5}$$

To demonstrate the relationships in (3), (4), and (5), consider the example of Fig. 5, where the i^{th} frame of LTE A is of class C_3. The total number of elapsed idle slots between the $(i-1)^{st}$ and i^{th} transmissions of A is

$$\begin{aligned} N_3(i) &= T_1 + T_2 + T_3 \\ &= B_3(i) + T_{def} + \rho_3(1) + T_{def} + \rho_3(2) + T_{def} + \rho_3 \\ &= \underbrace{B_3(i)}_{\text{backoff}} + \underbrace{3T_{def}}_{\text{defer}} + \underbrace{\rho_3(1) + \rho_3(2) + \rho_3}_{\text{observation slots}}. \end{aligned} \tag{6}$$

In this realization, the first intermediate transmission starts after A has completed its observation slots and hence $\rho_3(1) = \rho_3 = 3$ slots, whereas the second transmission starts before A completes the three observation slots and hence $\rho_3(2) = T_2 - T_{def} = 2$ slots. For the final set of elapsed idle slots, $\rho_3(3) = \rho_3 = 3$ slots because A must have sensed the channel for three slots designated by a C_3 transmission before it can complete the backoff and capture the medium. The backoff counter $B_3(i)$ is chosen uniformly from $[0, 15]$.

V. Priority Class Estimation

In real scenarios, a monitoring Wi-Fi terminal X is not aware of the priority class of an imminent LTE transmission. However, it can measure the elapsed idle slots $N(i)$ between two successive transmissions of the same LTE station, and also the number of intermediate transmissions ν_i that belong to other terminals. Knowing ν_i and $N(i)$, Wi-Fi X can use the relationships in (4) and (5) to compute the range of the elapsed idle slots $N_\ell(i)$, assuming that the class C_ℓ is a candidate. The range is given by $N_\ell(i) \in [N_\ell^{\min}(i), N_\ell^{\max}(i)]$ where

$$N_\ell^{\min}(i) = \sum_{j=1}^{\nu_i+1} (\rho_\ell(j) + T_{def}), \tag{7}$$

$$N_\ell^{\max}(i) = (q_{\ell_{\min}} - 1) + \sum_{j=1}^{\nu_i+1} (\rho_\ell(j) + T_{def}). \tag{8}$$

Here, the minimum and maximum possible backoff counters are set to zero and $(q_{\ell_{\min}} - 1)$, respectively. We here make the contention window size equal $q_{\ell_{\min}}$ because the prediction is only required for the new transmitted frames. For retransmitted frames, the class has to follow the same class used in the failed transmission which is supposed to be predicted previously. If the measured $N(i)$ from (3) belongs to $[N_\ell^{\min}(i), N_\ell^{\max}(i)]$, then C_ℓ is a candidate priority class that could lead to the observation of $N(i)$. Formally, the possible priority classes for the i^{th} LTE transmission are identified as follows:

1) Wi-Fi X senses the channel to record the number of intermediate transmissions ν_i and the idle periods T_j's. It then computes $N(i)$ via (3).
2) Wi-Fi X computes the elapsed idle slot range $[N_\ell^{\min}(i), N_\ell^{\max}(i)]$ for each class C_ℓ, using (7) and (8).
3) Wi-Fi X constructs vector $\mathbf{I}_C(i) = (I_1, I_2, I_3, I_4)$ where $I_\ell = 1$ if $N(i) \in [N_\ell^{\min}(i), N_\ell^{\max}(i)]$, otherwise $I_\ell = 0$.
4) If $\mathbf{I}_C(i) = (0,0,0,0)$ due to collisions, the presence of hidden terminals, or unsaturated traffic conditions (the LTE was not contending for a long time), the vector of candidate classes is set to $\mathbf{I}_C(i) = (1,1,1,1)$, i.e., all classes are possible.

The vector $\mathbf{I}_C(i)$ denotes the possible priority classes that can yield the counted number of idle slots $N(i)$. If the vector's cardinality is $|\mathbf{I}_C(i)| = 1$, then the priority class of the i^{th} transmission is predicted with certainty. However, in most cases, it is expected that $|\mathbf{I}_C(i)| > 1$. As an example of that, suppose we have $\nu_i = 0$, i.e., there is no intermediate transmissions. Then, for class C_ℓ we have

$$N_\ell^{\min}(i) = \rho_\ell + T_{def}, \quad N_\ell^{\max}(i) = \rho_\ell + T_{def} + q_{\ell_{min}} - 1. \tag{9}$$

Assuming $T_{def} \approx 2$ slots, this makes the ranges for the four classes be $[3,6], [3,10], [5,20]$ and $[9,24]$, respectively. If $N(i) = T_1$ is measured to be 7 slots, then we get a vector $\mathbf{I}_C(i) = (0,1,1,0)$, i.e., only classes 2 and 3 are candidates. In this case, we introduce two mechanisms for priority class estimation. The Transmit-First approach prevents oversleeping, whereas in the second approach, we apply Bayesian estimation to get a more accurate class estimation at the expense of some oversleeping.

A. The Transmit-First Class Estimation

In the first approach, the Wi-Fi terminal selects the highest priority class for which $I_\ell = 1$. Higher priority classes have a shorter channel occupancy time T_ℓ^{MCOP}, leading to shorter sleep times. This conservative approach allows the Wi-Fi terminal to save some energy while never missing transmission opportunities due to oversleeping. This comes at the expense of lower energy savings due to early wake up.

For instance, consider the aforementioned example where Wi-FI X inferred that $\mathbf{I}_C(i) = (0, 1, 1, 0)$, i.e, the imminent i^{th} LTE transmission belongs to either C_2 with $T_2^{MCOP} =$ 3ms, or C_3 with $T_3^{MCOP} =$ 8ms. If the Wi-Fi selected C_3 and stayed in sleep mode for 8ms, but a C_2 frame was transmitted, the Wi-Fi would miss the opportunity to contend after the first 3ms. Under the transmit-first approach, the Wi-Fi always chooses the highest class (C_2 in this case) and therefore sleeps for 3ms. This guarantees that the Wi-Fi will not oversleep. This strategy could lead to higher energy consumption if C_2 is selected but a C_3 frame is transmitted, as the Wi-Fi loses the opportunity to stay in sleep mode for an additional 5ms.

B. Bayes-based Estimation

In the second approach, the Wi-Fi estimates the priority class of the i^{th} LTE transmission using the knowledge of $N(i)$ and the empirical priority class distribution estimated based on prior transmission history. Specifically, we employ Bayesian estimation that maximizes the estimate of the posterior class probabilities given the prior distribution on $N(i)$. Formally, the estimated class $C_{\ell^*}(i)$ for the i^{th} transmission is given by

$$\begin{aligned} C_{\ell^*}(i) &= \underset{C_\ell \in \{C_1, C_2, C_3, C_4\}}{\operatorname{argmax}} P(C_\ell | N(i)) \\ &= \underset{C_\ell \in \{C_1, C_2, C_3, C_4\}}{\operatorname{argmax}} \frac{P(C_\ell) P(N(i) | C_\ell)}{P(N(i))}. \end{aligned} \quad (10)$$

In (10), the conditional probability $P(N(i)|C_\ell)$ can be computed based on the backoff counter $B_\ell(i)$. For a class C_ℓ for which $I_\ell(i) = 1$, i.e., $N(i)$ is within the expected idle slot range of that class, $B_\ell(i)$ can be computed by setting $N_\ell(i) = N(i)$ and solving for $B_\ell(i)$ using (4), where ν_i, T_j, and $\rho_\ell(j), \forall j$ are observable and fixed given a specific class in the i^{th} realization. Given that $B_\ell(i)$ is uniformly selected from $[0, q_\ell(i) - 1]$, where $q_\ell(i)$ denotes the contention window size for the i^{th} transmission, it follows that $P(N(i)|C_\ell) = P(B_\ell(i)|C_\ell) = 1/q_\ell(i)$. If $I_\ell(i) = 0$, i.e., an LTE frame of class C_ℓ is not feasible for the observed $N(i)$, then $P(N(i)|C_\ell) = 0$. The two cases can be summarized to

$$P(N(i)|C_\ell) = \frac{I_\ell(i)}{q_\ell(i)}. \quad (11)$$

To build the likelihood prior of $P(C_\ell)$, we use the relative sample frequencies obtained from the history of the LTE transmissions. Here, we do not apply any smoothing via a kernel density estimation process [14] because of the small number of classes (four in total) and a relatively large number of observations. We do, however, employ recent history to capture the temporal correlation of LTE transmissions. We expect that recent history reflects more accurately the probability of observing a frame that belongs to a specific class. For instance, a video transmission involves a sequence of frames that belong to C_3 or C_4, thus temporarily skewing the distribution on $P(C_\ell)$. To account for recent history, we calculate $P(C_\ell)$ as the weighted average of the relative sample frequencies over two time scales.

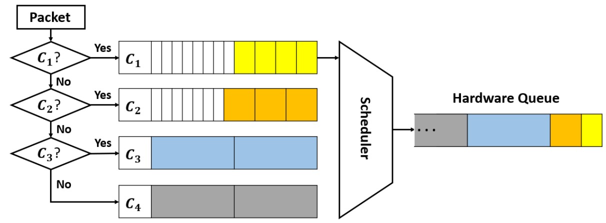


Fig. 6: Priority queuing model.

$$P(C_\ell) = \alpha(i) \frac{n'_\ell}{n'} + (1 - \alpha(i)) \frac{n_\ell}{n}, \quad (12)$$

where n'_ℓ/n' is the relative sample frequency of C_ℓ over the n' most recent observations, n_ℓ/n is the relative sample frequency of C_ℓ over all n observations, and $\alpha(i)$ is a weight factor that is optimized after every transmission is completed.

Determination of $\alpha(i)$: The weighting factor $\alpha(i)$ can be optimized to minimize the mean square error (MSE) of the class estimator. Here, we utilize the fact that the Wi-Fi can infer the actual LTE class at the end of each LTE transmission if it does not oversleep. This happens by measuring the time T^{MCOP} and attributing it to the corresponding class. Let $H_\ell(i) = 1$ if the Wi-Fi inferred at the end of the i^{th} transmission that the LTE used C_ℓ. The MSE is given by

$$MSE(i) = \tfrac{1}{4} \textstyle\sum_{\ell=1}^4 (P(C_\ell) - H_\ell(i))^2. \quad (13)$$

Substituting $P(C_\ell)$ from (12), yields

$$MSE(i) = \tfrac{1}{4} \textstyle\sum_{\ell=1}^4 \left(\left(\frac{n'_\ell}{n'} - \frac{n_\ell}{n} \right) \alpha(i) + \left(\frac{n_\ell}{n} - H_\ell(i) \right) \right)^2. \quad (14)$$

To minimize $MSE(i)$, we differentiate with respect to α

$$\tfrac{d(MSE(i))}{d(\alpha(i))} = \tfrac{1}{2} \textstyle\sum_{\ell=1}^4 \left(\left(\frac{n'_\ell}{n'} - \frac{n_\ell}{n} \right)^2 \alpha(i) + \left(\frac{n'_\ell}{n'} - \frac{n_\ell}{n} \right) \left(\frac{n_\ell}{n} - H_\ell(i) \right) \right). \quad (15)$$

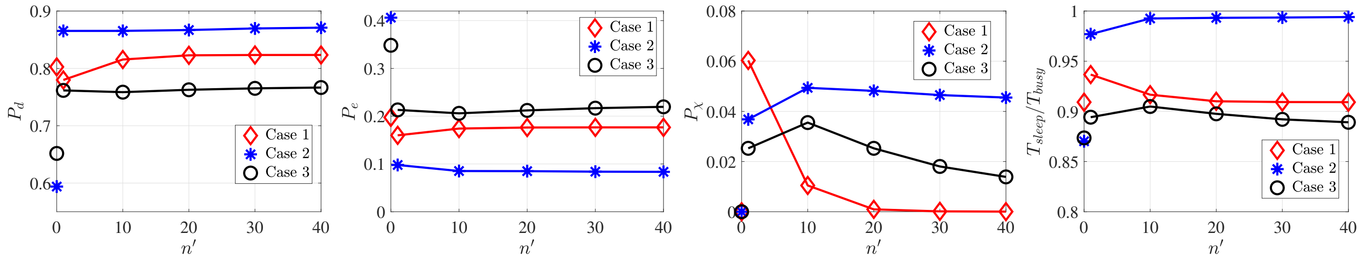
Solving $\frac{d(MSE(i))}{d(\alpha(i))} = 0$ yields

$$\alpha(i) = \frac{\sum_{\ell=1}^4 \left(\frac{n'_\ell}{n'} - \frac{n_\ell}{n} \right) \left(H_\ell(i) - \frac{n'_\ell}{n} \right)}{\sum_{\ell=1}^4 \left(\frac{n'_\ell}{n'} - \frac{n_\ell}{n} \right)^2}. \quad (16)$$

The updated $\alpha(i)$, evaluated by minimizing the MSE at the i^{th} transmission, is used for estimating the priority class of the $(i+1)^{th}$ transmission. Finally, the Wi-Fi computes

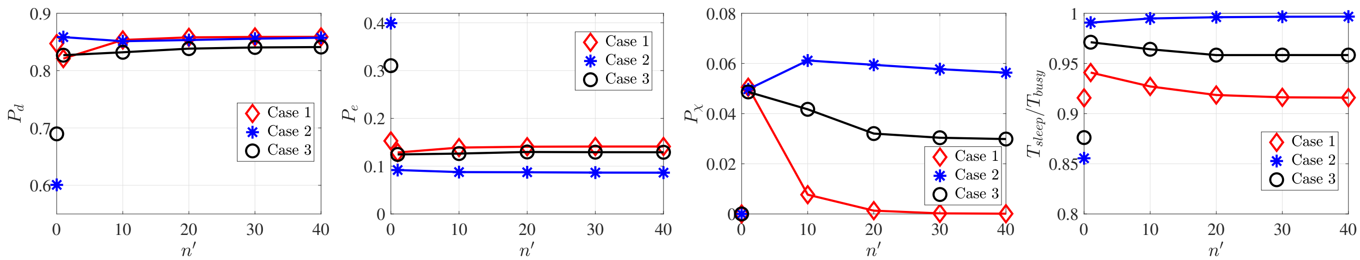
$$P(N(i)) = \textstyle\sum_{\ell=1}^4 P(C_\ell) P(N(i)|C_\ell), \quad (17)$$

where $P(C_\ell)$ is given by (12) and $P(N(i)|C_\ell)$ is given by (11). This enables the Wi-Fi terminal to apply (10) and select the class $C_{\ell^*}(i)$ with the highest probability. Once $C_{\ell^*}(i)$ is selected, Wi-Fi transitions to sleep mode for the designated $T_{\ell^*}^{MCOP}$. Note that if H_ℓ cannot be inferred due to oversleeping, the optimization step in (15) is skipped and the previous value of $\alpha(i)$ is maintained.



(a) P_d. (b) P_e. (c) P_χ. (d) T_S/T_{busy}.

Fig. 7: Estimation performance for the fair queuing model as a function of the history length n'.



(a) P_d. (b) P_e. (c) P_χ. (d) T_S/T_{busy}.

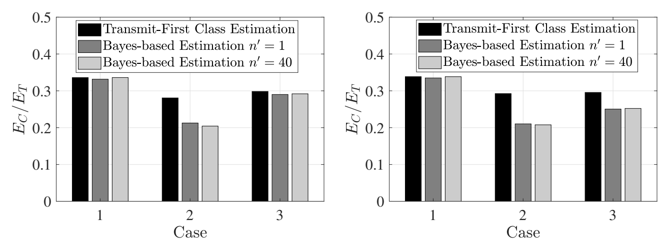
Fig. 8: Estimation performance for the priority queuing model as a function of the history length n'.

VI. Performance Evaluation

To validate the proposed power saving mechanisms, we implemented an event-based simulation. Three LTE stations and one Wi-FI were placed in the same collision domain. All terminals were assumed to be backlogged. The LTE stations followed the LAA-LTE specification, whereas the Wi-Fi terminal implemented the IEEE 802.11ac protocol. We ran our simulations for 30,000 events, where each event represents one LTE transmission attempt.

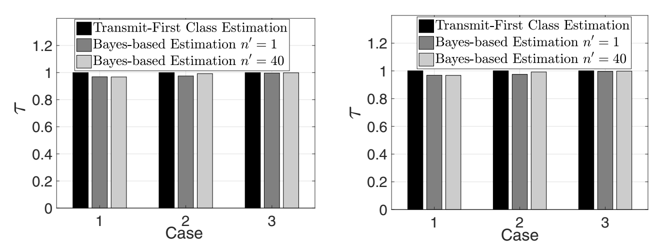
Class traffic generation: We considered a priority queuing model where we have one queue for each class as shown in Fig. 6. The frames were assumed to follow a Poisson arrival process. We denote by λ_ℓ the arrival rate for frames of class C_ℓ at the corresponding queue. The four queues are combined into one final queue. LTE frames are transmitted in the same order they are in the final queue. Frames are transferred from their original queues to the final queue using: (i) fair queuing using the expected end times for each transmission, and (ii) priority queuing in which higher priority frames are always transmitted first. Within each scenario, we performed our simulation for three different cases that reflect different practical scenarios. Case 1 represents the situation when frames belonging to higher priority classes are the majority compared to lower priority classes. Case 2 implements the opposite scenario. Whereas for case 3, frames of different classes appear equiprobably. The key parameters of our evaluation are P_d the probability of correctly estimating T_ℓ^{MCOP}, the probability of an early wake up P_e, and the probability of oversleeping P_χ.

Results: Figure 7(a) shows P_d as a function of the recent history length n' for the fair queuing approach. We show that Bayes estimation yields around 80% estimation accuracy for different cases. We observe that the accuracy is slightly improved when n' is increased. This happens because when



(a) Fair queuing. (b) Priority queuing.

Fig. 9: E_C/E_T for different cases.



(a) Fair queuing. (b) Priority queuing.

Fig. 10: τ for different cases.

n' is small (we give more weight to the few previous transmissions), this may be not enough to reflect the real class distribution unlike the case when n' is sufficiently increased. We further observe that when the majority of the traffic is either C_3 or C_4 (case 2), the estimation is more accurate because most misclassifications happen between those two classes which have the same T_ℓ^{MCOP}. Finally, we show the performance of the transmit-first strategy ($n' = 0$). Although this strategy does not take into account the prior history, it performs acceptably in estimating the traffic class, especially for case 1, solely based on the $N(i)$ range.

In Fig. 7(b), and Fig. 7(c), we show the impact of erroneous class estimation on the energy conservation and the loss of transmission opportunities. We observe that the majority of the false estimation $(1 - P_d)$ results in early wake up (P_e) for cases 1 and 3 and is almost equally divided for case 2. The higher percentage of early wake ups is justified by the difference in T_ℓ^{MCOP} between the classes. When a lower priority class (classes 3 and 4) is misclassified to a higher priority one, this leads to an early wake up. However, when it is misclassified to another lower priority class, it does not lead to oversleeping because $T_3^{MCOP} = T_4^{MCOP}$. For the oversleeping probability, we notice that it decreases significantly with the increase in n' for cases 1 and 3. Moreover, in Fig. 7(c), we observe that the transmit-first approach $(n' = 0)$ has a zero oversleeping probability as expected. In Fig. 7(d), we study the ratio between the time slept by the Wi-Fi (T_S) and the actual time that the channel is occupied by the LTE (T_{busy}). We notice that sleeping time decreases with the increase in n' due to the decrease in the oversleeping time. We also observe that the distribution that favors higher classes (case 2) stays closer to the true busy state of LTE, but tends to oversleep. Whereas in the other two cases, early wake up is the most likely scenario as n' increases.

We repeated the first set of experiments for the priority queuing. Fig. 8 shows an increase in the estimation accuracy (measured by P_d) compared to the fair queuing approach (Fig. 7). This occurs because consecutive LTE frames tend to belong to the same class when the priority queuing approach is used, so recent history is a good predictor of the next frame. The trends in early wake up and oversleeping remain the same for the three class distributions. We further evaluated the energy efficiency achieved by our proposed mechanism by computing the ratio of the energy consumed when the Wi-Fi goes to sleep during the LTE transmission denoted by E_C over the energy consumed when Wi-Fi nodes continue to sense during LTE transmissions, denoted by E_T (smaller ratios indicate higher energy efficiency). For our simulations, we fixed the class of the Wi-FI AP to C_1 with $T_\ell^{MCOP} = 1.504ms$. Both E_C and E_T are calculated from (2), with $P_A = 1.687$W, $P_I = 1.038$W and $P_S = 0.088$W [4]. Figures 9(a) and 9(b) show over 60% energy savings for both the Bayes estimation and transmit-first mechanisms. As expected, the Bayes estimation achieves a better performance, as it gives a more accurate class prediction. Moreover, the transmit-first approach achieves significant savings without sacrificing any transmission opportunities for the Wi-Fi.

Finally, we evaluated the throughput loss of the Wi-Fi due to oversleeping. We define τ as the ratio between the number of successful transmission attempts of the Wi-Fi terminal with and without our scheme. In Fig. 10(a) and Fig. 10(b), we show τ for each traffic case under fair and priority queuing, respectively. We observe that the transmit-first scheme does not affect the terminal throughput as it avoids oversleeping. We highlight that early wake up, unlike oversleeping, does not affect contention opportunities. When the Bayes estimation approach is followed, the throughput loss is very small (less than 4%) for all three cases and queuing models as we note in Fig. 7 and Fig. 8. This is because the misclassification mainly leads to an early wake up, while the oversleeping probability is negligible. Note that the less-than 4% loss in throughput yields almost 10% additional gains in energy efficiency compared to the transmit-first approach for case 2.

VII. Conclusions

We presented a new method for achieving implicit coordination between coexisting systems which enabled Wi-Fi terminals transition to sleep mode when LTE stations are transmitting. We proposed a mechanism that allows the Wi-Fi terminal predict the priority class of an imminent LTE transmission by analyzing the idle periods of the LTE and the prior transmission history. Our method led to over 60% in energy savings in various traffic scenarios without notable loss in throughput. Although we presented our method from the perspective of the Wi-Fi terminal, the same prediction approach can be adopted by LTE stations to be set to sleep mode during Wi-Fi transmissions.

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