Enabling Media Streaming over LTE-U Small Cells

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***Abstract*—In an attempt to face the anticipated spectrum crunch and inspired by the possibility of extending LTE-A to the unlicensed spectrum (LTE-U), in this paper we devise an adaptive channel assignment scheme for video streaming over LTE-U small cells. The proposed scheme adaptively assigns video frames to a subset of monitored channels with the objective of reducing possible starvation instants at user equipments (UEs), and hence maintaining continuous video playback. Specifically, considering coexisting LTE-U small cells and Wi-Fi networks, and leveraging the carrier aggregation (CA) feature in LTE-A, our scheme takes into account the quality of monitored channels, the occupancy of the playback buffers at the UEs, the deadlines and priorities of transmitted video frames, as well as the activity of Wi-Fi users when optimizing the assignment of video frames to channels in the licensed and unlicensed spectrum. According to the numerical results, the proposed scheme returns higher utility, and hence higher probability of correctly receiving video frames, compared to traditional assignment schemes.**

I. Introduction

The rapid proliferation in the capabilities and number of smart mobile devices combined with a similar trend in bandwidth-hungry applications, result in a looming spectrum crisis. For this reason, industry is gearing to meet the 1000x challenge, where the demand for wireless spectrum in 2020 is expected to be 1000x of that in 2010. Among different traffic types transmitted over wireless channels, video traffic is considered the main reason for the expected spectrum crisis, as it requires relatively high data rates with strict bounds on packet loss rates, delay, and delay jitter (especially for real-time video communications). According to Cisco, by 2018 over two-thirds of the world's mobile data traffic is expected to be video traffic [1]. Not to overwhelm band-limited networks, video compression algorithms are always employed to reduce the storage and transport requirements of streamed video. This is typically done by removing spatial and temporal redundancies inherent in video sequences, which in turn results in interdependencies between different types of video frames. Specifically, independently encoded video frames are needed to encode/decode consecutive dependent frames. Such interdependency, place additional burden on the design of efficient video communication systems.

Recently, extending LTE-A to the unlicensed spectrum (LTE-U) has gained lots of attention compared to other approaches proposed to face the 1000x challenge [2]. LTE-U exploits the supplemental downlink (SDL) and carrier aggregation (CA) features in LTE-A systems to offload data traffic (mostly multimedia traffic) of 4G LTE-A systems from the licensed 4G bands (400 MHz - 3.8 GHz) to the unlicensed 5 GHz spectrum, where about 500 MHz spectrum is available. The motivation behind this approach is to enhance the downlink (DL) throughput of user equipments (UEs) using the same network. To maintain reliability in LTE-U, all control information (also UL data) is communicated over the robust interference-free licensed 4G spectrum, where cellular operators have the exclusive right to use the spectrum [2]. Only when needed, the DL can be supplemented by the unlicensed spectrum through CA to create a fatter data pipe. Although there exist multiple proposals for LTE-U (non LBT-based and LBT-based or LAA) [3], in this paper we focus on the LBT-based LTE-U and call it, for simplicity, LTE-U throughout the paper.

The coexistence problem of Wi-Fi networks and LTE-U small cells has recently been addressed [4–11]. The performance of coexisting LTE-U and Wi-Fi systems was evaluated via simulations in [8] and experimentally in [5]. To enable the coexistence of Wi-Fi and LTE-U small cells, the authors in [6] exploited the concept of almost blank subframes (ABS), where an LTE cell gives up some of its subframes to Wi-Fi users. In [10], the authors studied the problem of sharing the unlicensed spectrum between strategic operators using game theoretic techniques. They found out that without coordination, each operator will transmit at the maximum power, causing high interference to coexisting operators. On the other hand, if operators coordinate with each other in selecting different parts of the spectrum, they can avoid mutual interference and hence increase the overall utility. In [7], the authors developed an interference analysis technique based on a fluid model to study the inter-system interference between Wi-Fi and LTE-U. In [12], the authors proposed several stochastic resource allocation formulations to minimize the cost of composing a virtual LTE-U network from a set of Wi-Fi access points (APs).

In this paper, we consider video streaming over LTE-U small cells. In addition to the classical challenges faced by video streaming over wireless links (e.g., limited throughput, fast-varying BER, fading, etc.), there are some unique challenges that result from LTE-U/Wi-Fi coexistence. These challenges are related to the nature of operations of the two schemes, since Wi-Fi networks rely on contention-based channel access (i.e., CSMA/CA), while LTE-U small cells are schedule-based (resources are periodically assigned to UEs every 1 ms). Furthermore, channel availability in the unlicensed band is dynamic due to random channel access of the Wi-Fi users (WUs). Clearly, this also makes video transmission on these channels by the HeNBs quite challenging. Losing important (referenced) video frames, due to collisions with Wi-Fi signals, will not only cause degradation in the quality of the

This research was supported by the National Science Foundation (grants IIP-1265960, IIP-1432880, CNS-1513649, and IIP-1535573). Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of NSF.

978-1-4673-9814-5/16/$31.00 ©2016 IEEE

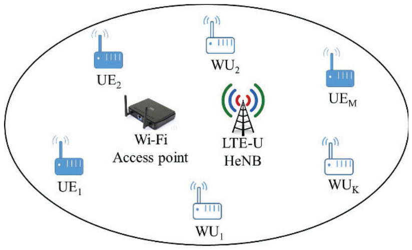

Fig. 1. System model for an LTE-U small cell, that is composed of an HeNB and M UEs, coexists with a Wi-Fi network, that is composed of a Wi-Fi AP and K WUs.

reconstructed video due to error propagation, but might lead to severe interruptions at UEs because of the interdependencies between video frames.

To address the aforementioned problems, we propose an adaptive channel assignment scheme for video streaming over LTE-U small cells. The proposed scheme adaptively assigns video frames to available channels, leveraging the CA/SDL features in LTE-U. The objective of our adaptive scheme is to reduce possible starvation instants at UEs, and hence maintain continuous video playback. We formulate the frames' assignment problem as an optimization problem, which takes into account the quality of the monitored channels, the Wi-Fi activity on the unlicensed channels, the occupancy of the playback buffers at UEs, in addition to the deadlines and priorities of transmitted video frames. The assignment process targets the maximization of the probability of correct reception of video frames. To enable online-monitoring of channels, we exploit recent developments in self-interference cancellation (SIC) techniques and full-duplex (FD) capabilities [13], where the HeNB carries out in-band spectrum sensing for the unlicensed channels [14, 15]. In [16], the authors proposed an adaptive scheme that selects the user to be served according to buffers' occupancy, channel quality, and the sensitivity of scheduled video frames.

The rest of the paper is organized as follows. The system model is described in Section II. The adaptive assignment scheme for LTE-U small cells is proposed and discussed in Section III. We evaluate the performance of the proposed scheme and conclude the paper in Sections IV and V, respectively. Table I lists the main notation and symbols used in this paper. To the best of our knowledge, this is the first paper to consider video communications over LTE-U small cells.

II. System Model

As shown in Figure 1, we consider an LTE-U small cell that coexists with a Wi-Fi network. The LTE-U cell is composed of an HeNB and M UEs. The Wi-Fi network consists of a Wi-Fi AP and K WUs. The HeNB communicates with UEs on the licensed spectrum for both control and UL data transmissions. It can transmit DL data on both licensed and unlicensed bands by leveraging SDL/CA features. The unlicensed spectrum is also used by WUs for communications in a contention-based fashion. Such communications is facilitated by a CSMA/CA protocol.

We assume that the spectrum available to a given HeNB is divided into two bands, a licensed band with bandwidth B_L and an unlicensed band with bandwidth B_U. The licensed and unlicensed bands are divided into N_L and N_U channels, respectively. For simplicity, we assume that channels have the same bandwidth. We assume that HeNB can exploit CA to aggregate up to $N_a < N_L + N_U$ channels (on the licensed and unlicensed bands) to communicate with an UE. Note that the number of aggregated channels, N_a, is relatively small (e.g., $N_a = 3$ or 4) and should comply with the LTE-A standards.

Symbol	Description
i, j, k	Index of channel, UE, and video frame, respectively
M, K	Number of UEs and WUs in the network, respectively
$\tilde{M}$	Number of active UEs streaming video content
B_L, B_U	Bandwidth of licensed and unlicensed spectrum, respectively
N_L, N_U	Number of licensed and unlicensed channels, respectively
N_a, N_m	Number of aggregated and monitored channels, respectively
$\mathbf{p}_t$	Channel belief prob. vector at time t
$p_{t,i}$	Prob. that the ith channel is idle at time t
$\mathbf{p}_{t+T}$	Updated belief vector at time $t+T$
$\mathbf{b}_t$	BER vector at time t
$b_{t,i}$	BER experienced on the ith channel at time t
$\mathbf{b}_{t+T}$	Updated BER vector at time $t+T$
N_p	Number of packets per video frame
$N_{\text{tot},i}$	Packet size in bits transmitted on channel i
N_{in}	Payload size per packet
$N_{\text{ov},i}$	Number of FEC parity bits per packet on channel i
$N_{c,i}$	Number of correctable bits per packet on channel i
$\boldsymbol{\tau_j}$	Deadline vector for user j for the three frame types
τ_{kj}	Deadline of frame type k of user j
τ^y_{kj}, τ^d_{kj}	Display and decoding deadlines of frame type k of user j, respectively
τ^u_j	Underflow deadline of user j
$P^f_{C_{ki}}$	Prob. of correct reception of frame k on channel i
$P^p_{C_{ki}}$	Prob. of correct reception of a packet in video frame k transmitted over channel i
E_{ki}	Cost matrix's element that exists in row k and column i
T	Transmission time
P_f	False-alarm probability

TABLE I. Symbols used in the paper.

We assume that the HeNB is serving $\tilde{M} < M$ UEs, who are streaming different video sequences over multiple channels. At each decision instant, the HeNB decides to serve a single UE according to a certain criterion (Section III). The HeNB distributes video frames of this specific user among multiple licensed and unlicensed bands. Let $N_m \geq N_a$ be the number of channels that are continuously monitored by the HeNB, which could belong to the licensed or unlicensed spectrum or both. Our objective is to determine, at each transmission instant, which UE to be served by the HeNB and optimally assign the UE's video frames to the different possible channels. Optimality here is in the sense of maintaining continuous playback at the different UEs.

We define two channel metrics that are monitored by the HeNB (and the corresponding communicating UE). The first metric is the channel belief $\mathbf{p}_t = [p_{t,1}, p_{t,2}, \ldots, p_{t,N_m}]$, where $p_{t,i}$ is the probability that the ith channel is idle at time t, as believed by the HeNB. Note that $p_{t,i} = 1\,\forall t$, for licensed channels. The HeNB/UEs starts communications over the ith channel (probably after an initial sensing period) with an initial belief, at $t = 0$, of $p_{0,i} = 1 - P_f$, where P_f is the false-alarm probability. After each transmission, and according to the transmission/sensing outcomes (as described later), the HeNB updates its belief about the channel availability. The sensing outcomes could be free ‘F’ or occupied ‘O’, while the transmission outcome could be ACK ‘A’ or NACK ‘N’ (i.e., ACK timeout). In this paper, we assume imperfect sensing, where declaring free/occupied by the HeNB does not reflect the actual status of the channel. However, this decision is accompanied by false-alarm and mis-detection probabilities. The second metric is the channel quality. Let $\mathbf{b}_t = [b_{t,1}, b_{t,2}, \ldots, b_{t,N_m}]$ be the BER vector, where $b_{t,i}$ is the BER of channel i at time t. At the end of each LTE subframe transmission, the UE informs the HeNB with the channel quality (reflected in the BER value, via the PUCCH channel). Such an act allows HeNB to continuously monitor the channel quality.

We assume that each video frame is packetized into N_p packets. For $i \in \{1, 2, \ldots, N_m\}$, $N_{\text{tot},i} = N_{\text{in}} + N_{\text{ov},i}$ is the packet size in bits when transmitted over the ith channel, where N_{in} is a fixed number of information bits per packet, while $N_{\text{ov},i}$ is the forward error correction (FEC) overhead in bits per packet. For a certain BER and a certain FEC algorithm, the maximum number of correctable bits per packet is $N_{c,i}$.

III. Adaptive Video Frames’ Transmission Scheme

A. Adaptive Scheme Description

Algorithm 1 Adaptive assignment algorithm

1: HeNB executes the initial sensing/probing phase
2: **for** each channel $i, i = 1, 2, \ldots, N_m$ **do**
3: **if** channel i is an unlicensed channel **then**
4: HeNB carries out spectrum sensing
5: **if** channel i is sensed free **then**
6: $p_{0,i} = 1 - P_f$. HeNB probes channel $i \rightarrow b_{0,i}$
7: **else**
8: Skip channel i
9: **end if**
10: **else**
11: $p_{0,i} = 1$. HeNB probes channel $i \rightarrow b_{0,i}$
12: **end if**
13: **end for**
14: **for** each UE $j, j = 1, 2, \ldots, \tilde{M}$ **do**
15: UE j associate with HeNB and sends initial τ_j
16: **end for**
17: HeNB selects the UE to serve: $\hat{j} = \arg\min\left(\min(\tau_1), \ldots, \min(\tau_{\tilde{M}})\right)$
18: HeNB assigns frames of UE $\hat{j}$ to available channels using (5):
19: **for** each frame $k, k \in \{I, P, B\}$ **do**
20: **while** frame k is being transmitted to channel $i, i = 1, 2, \ldots, N_a$ **do**
21: **if** Frame k is assigned to a licensed channel **then**
22: Out-of-band sensing for an unlicensed channel
23: Belief update of sensed channel (free/occupied)
24: **else**
25: In-band sensing
26: Belief update of sensed channel (free/occupied)
27: **end if**
28: **end while**
29: HeNB receives the PUCCH from UE
30: **if** selected channel is licensed **then**
31: $p_{t+T,i} = 1$
32: **else** Belief update (ACK/NACK)
33: **end if**
34: Update the BER vector $\mathbf{b}_{t+T} \forall$ licensed and unlicensed channels
35: **end for**
36: **if** video sequence has ended **then**
37: End
38: **else** Update the frames deadlines and go to step 17
39: **end if**

Before describing the adaptive video frames assignment scheme, we briefly explain different types of video frames. Common video compression standards define three types

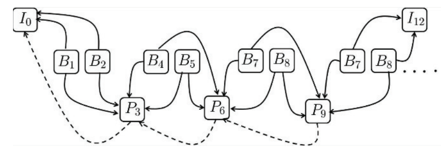

Fig. 2. A possible GoP structure.

of video frames, namely I-frame (Intra-coded picture), P-frame (Predicted picture), and B-frame (Bi-predictive picture). Among these frames, I-frames are the most important frames that are crucial for other frames to be decoded (see Figure 2). In other words, I-frames are images that are independently encoded, while P-frames are encoded by referencing a previous I or P frame. Furthermore, B-frames contain only the differences between the current frame and the preceding and following I and/or P frames, to achieve the highest compression ratio.

A video stream is divided into a sequence of group-of-pictures (GOP). The structure of the GOP determines the number of P and B frames between two successive I frames. Specifically, a single GOP is defined by two parameters (M_g, N_g), where M_g is the distance between successive I frames (i.e., GOP size). The distance between consecutive P frames, which is equivalent to the distance between an I frame and the following P frame, is denoted by N_g. An example of a widely used GOP with parameters $(M_g = 12, N_g = 3)$ has the following structure $I_0 B_1 B_2 P_3 B_4 B_5 P_6 B_7 B_8 P_9 B_{10} B_{11}$.

Algorithm 1 shows the main steps of the proposed scheme, where the HeNB starts with an initial phase by executing spectrum sensing and probing to get information about the monitored channels. The output of this initial phase is two vectors, namely the initial belief vector $\mathbf{p}_0 = [p_{0,1}, p_{0,2}, \ldots, p_{0,N_m}]$ and the initial BER vector $\mathbf{b}_0 = [b_{0,1}, b_{0,2}, \ldots, b_{0,N_m}]$. Although the HeNB does not execute spectrum sensing for the licensed channel, for simplicity, we include the belief of these channels in the belief vector $\mathbf{p}_0$ with values equal to one.

After the association process, the HeNB starts the communication process with the UEs. According to the UEs’ video sequences (subscription type, requested video quality, etc.), the HeNB takes as an input the available frames (i.e., I, P, or B frames) to be transmitted to UEs, as well as the frames deadlines (explained later). Specifically, let $\tau_j = [\tau_{Ij}, \tau_{Pj}, \tau_{Bj}]$ be the deadline vector for the different types of video frames, where $\tau_{kj}, k \in \{\text{I, P, B}\}, j \in \left\{1, 2, \ldots, \tilde{M}\right\}$ be the time-window constraint on frame k of user j. Given the deadlines of the video frames, the HeNB decides which UE to serve at this transmission instant according to the following equation:

$$j = \arg\min\left(\min(\tau_1), \min(\tau_2), \ldots, \min(\tau_{\tilde{M}})\right). \qquad (1)$$

The criterion for choosing the UE to be served is selecting the UE with the smallest frame deadline, not to affect its decoding process and hence avoid possible starvation. Once the UE is selected, the objective of the adaptive assignment scheme is to assign frame $k, k \in \{I, P, B\}$ to channel $i, i \in \{1, 2, \ldots, N_m\}$ according to the HeNB belief about the Wi-Fi activity and channel conditions, while taking into account the playback and decoding deadlines. After that, the HeNB transmit UE’s video frames on the assigned licensed and unlicensed channels. In parallel with this transmission, the

HeNB carries out in-band and out-of-band spectrum sensing for the unlicensed channels only to monitor the activity of the WUs. Specifically, For unlicensed channels (currently used for video frames' transmission), the HeNB utilizes SIC techniques to execute simultaneous transmission-and-sensing (i.e., in-band sensing). On the other hand, for licensed channels, the HeNB executes out-of-band sensing to monitor other unlicensed channels. The reason for this action is to keep updated profiles for the different unlicensed channels, that can be good for CA in future transmissions (in case of collision with WUs). According to the outcomes of in-band and out-of-band sensing, the HeNB updates its belief about the WU activity in the sensed channels.

After transmitting video frames to the UE, the HeNB receives important information in the PUCCH channel. First, the HeNB uses the ACK/NACK information in the PUCCH channel to anticipate whether the WU was active or not in the used unlicensed channels. The HeNB uses this information (combined with the free/occupied outcome) to update its belief about channel availability [17]. Second, the HeNB uses the BER value in the PUCCH channel to update its knowledge about the channel quality. Finally, the HeNB repeats the process again with the updated belief, channel quality, frames' deadlines vectors.

B. Frames' Assignment Optimization Problem

The goal of the optimization problem is to guarantee the continuity of video playback at the UE, through careful assignment of video frames to different channels according to different parameters. First, we explain video frame deadlines considered in the analysis. The first deadline is the playback time of a video frame, which is simply the time the frame is displayed on the screen. Let's take the $(M_g = 12,\ N_g = 3)$ GOP as an example. Recall that, the aforementioned GOP has the following structure: $I_0B_1B_2P_3B_4B_5P_6B_7B_8P_9B_{10}B_{11}$. Denote the display deadline of frame type k, $k = \{\text{I, P, B}\}$ of user j, by τ^y_{kj}. In this case, $\tau^y_{I_0j} < \tau^y_{B_1j} < \ldots < \tau^y_{B_{11}j}$, which means that the frames' order plays a crucial role in determining our proposed selection criterion.

Due to frames' interdependency, some frames cannot be decoded without the correct decoding of other frames. Hence, the second deadline to be included is implied in the so called transmission order of video frames, that is mainly influenced by the interdependency between frames. A frame decoding deadline is defined as the time instant at which a frame is needed to decode other dependent frames. For example, in the $(M_g = 12,\ N_g = 3)$ GOP, the receiver cannot decode (and hence cannot display) B_1 frame unless it receives and correctly decodes I_0 and P_3. Hence, according to the decoding deadline, the frames should be ordered as follows: $I_0P_3B_1B_2P_6B_4B_5P_9B_7B_8I_{12}B_{10}B_{11}$. Denote the decoding deadline for frame type k, $k = \{\text{I, P, B}\}$, of user j by τ^d_{kj}. In this case, $\tau^d_{I_0j} < \tau^d_{P_3j} < \tau^d_{B_1j} < \tau^d_{B_2j} < \ldots < \tau^d_{B_{11}j}$.

The third deadline is mandated by the occupancy of the playback buffer at the UE. Simply, the receiver should keep a minimum number of frames in the buffer to avoid underflow situations. Underflow happens when the number of correctly decoded received frames in the playback buffer of the UE falls below that number. This can be used as indication before starvation (i.e., no more frames to display, hence playback interruption), which typically happens when the UE cannot find an idle/good channel to use. Hence, the buffer underflow deadline is the maximum time (measured as a function of the playback buffer occupancy) after which underflow occurs. Denote the buffer underflow deadline of user j by τ^u_j.

Now, we need to combine different frames' deadlines to define the constraints of our selection criterion. First, for I and P frames, the deadline constraint should be written as follows:

$$\tau_{kj} = \min(\tau^y_{kj}, \tau^d_{kj}, \tau^u_j),\ k \in \{I, P\}, j \in \{1, 2, \ldots, \tilde{M}\}. \quad (2)$$

On the other hand, the deadline constraint for B frames can be expressed as $\tau_{Bj} = \min(\tau^y_{Bj}, \tau^u_j)$. Next, we formulate the optimization problem. The objective of the HeNB is to assign video frames of a given UE to different licensed and unlicensed channels so that the probability of correct reception is maximized while taking into account channel availability, channel quality, and frames' deadlines. Formally:

$$\begin{aligned} \underset{X_{ki}}{\text{maximize}} \quad & \sum_{k\in\{\text{I, P, B}\}} (1-\tau_{kj}) \sum_{i\in\{1,2,\ldots,N_a\}} X_{ki} \times P^f_{C_{ki}} \\ \text{subject to} \quad & \sum_i X_{ki} = 1\ \forall k, \qquad \sum_k X_{ki} = 1\ \forall i \\ & X_{ki} \in \{0, 1\}\ \forall k, i \end{aligned} \quad (3)$$

where $X_{ki}, k \in \{\text{I, P, B}\}, i \in \{1, 2, \ldots, N_a\}$, are binary decision variables. $X_{ki} = 1$ means that frame k is assigned to channel i. $P^f_{C_{ki}}$ is the probability of correct reception of video frame of type k over channel i. The parameter $(1-\tau_{kj})$ gives higher weights to video frames with strict delays (display and decoding deadlines and playback buffer underflow). The first constraint ensures that each video frame will be assigned to only one channel, while the second constraint ensures that each channel will be assigned only one video frame.

Now, we explain the formulation of the probability $P^f_{C_{ki}}$. A video frame consists of N_p packets, where each packet consists of $N_{\text{tot},i}$ bits. A given packet is correctly received as long as the maximum number of bits in error is $N_{C,i}$ (which is determined by the used FEC). Hence, the probability of correct reception of an arbitrary packet, $P^p_{C_{ki}}$, can be written as:

$$P^p_{C_{ki}} = p_{t,i} \sum_{l=0}^{N_{C,i}} \binom{N_{\text{tot},i}}{l} (b_{t,i})^l (1-b_{t,i})^{(N_{\text{tot},i}-l)}. \quad (4)$$

$P^p_{C_{ki}}$ takes into account the channel BER (i.e., $b_{t,i}$) and the HeNB belief about the channel status (i.e., $p_{t,i}$). Reformulating our assignment optimization problem in (3), by considering multiple packets per frame (a frame is correctly received if every packet in this frame is correctly received), we get:

$$\begin{aligned} \underset{X_{ki}}{\text{maximize}} \quad & \sum_{k\in\{\text{I, P, B}\}} (1-\tau_{kj}) \sum_{i\in\{1,2,\ldots,N_a\}} X_{ki} \times p_{t,i} \\ & \left[\sum_{l=0}^{N_{C,i}} \binom{N_{\text{tot},i}}{l} (b_{t,i})^l (1-b_{t,i})^{(N_{\text{tot},i}-l)} \right]^{N_p} \\ \text{subject to} \quad & \sum_i X_{ki} = 1\ \forall k, \qquad \sum_k X_{ki} = 1\ \forall i \\ & X_{ki} \in \{0, 1\}\ \forall k, i. \end{aligned} \quad (5)$$

The aforementioned assignment optimization problem can be solved in a polynomial time using the Hungarian method [18]. Specifically, the problem can be represented by a cost matrix, where the element in the kth row and ith column represents the cost of assigning frame k to channel i. In our problem, the entries in the kth row and ith column, E_{ki}, can be written as:

$$E_{ki}{=}{-}(1-\tau_{kj})p_{t,i}\left[\sum_{l=0}^{N_{C,i}}\binom{N_{\text{tot},i}}{l}(b_{t,i})^{l}(1-b_{t,i})^{(N_{\text{tot},i}-l)}\right]^{N_p}.$$

The Hungarian method is based on the fact that adding a number to (or subtracting a number from) all the entries of a given row or column of the cost matrix, will not change the optimal assignment. The steps of the Hungarian method can be summarized as follows. First, add dummy rows/columns, if necessary, to ensure that the cost matrix is square, where the elements of the dummy rows/columns are the same as the largest number in the matrix. Second, subtract the minimum value of each row (column) from that row (column). Third, cover all the zero elements with the minimum number of horizontal/vertical lines. If the number of lines equal to the number of rows (or columns), then this is the optimal assignment. If not, then subtract the smallest entry not covered by any line from each uncovered row and add it to each covered column. Repeat these steps until the number of lines is equal to the number of rows.

IV. Numerical Results

Unless otherwise is mentioned, we use the following parameters for the numerical results. The packet size is set to $N_{\text{tot},i} = 1024$ bits $\forall i$, the number of packets per a video frame is $N_p = 100$ packets, and the number of correctable bits per packet is $N_{C,i} = \lfloor 10\% N_{\text{tot},i} \rfloor$. We set $\tilde{M} = 1$ and the number of aggregated channels $N_a = 3$. Without loss of generality, in this section, we use the fact that I frames are of a higher priority than P frames, which are of higher priority than B frames. Specifically, we arbitrarily set the priority ratio for the I, P, and B frames as $5:3:2$.

Figure 3 shows video frames assignment to three channels versus the BER of channel 1 (i.e., $b_{t,1}$). Specifically, we fix the HeNB's belief about all channels to be 0.9 and set the BER values at channels 2 and 3 to be, $b_{t,2} = 2 \times 10^{-3}$ and $b_{t,3} = 9 \times 10^{-3}$, respectively. We found that at low values of $b_{t,1}$, the I frame is assigned to channel 1 because it has the lowest BER value. At the same time, frames P and B are assigned to channels 2 and 3, respectively, since $b_{t,2} < b_{t,3}$. As $b_{t,1}$ increases, channel 1 quality decreases until it reaches to a threshold value $b_{t,1}^{*}$. At this point, $b_{t,1} > b_{t,2}$, and hence the adaptive scheme swaps frames I and P since frame I has more strict deadline. $b_{t,1}$ continues to increase until it reaches threshold $b_{t,1}^{**}$. At this point, channel 1 has the worst quality (compared to other channels), hence the adaptive scheme swaps frames P and B, as shown in Figure 3 to enhance the probability of frames' correct reception.

Figure 4 shows another video frames assignment realization, where we vary the HeNB's belief value about channel 1 (i.e., $p_{t,1}$). We set the BER values for all channels to be 10^{-3} and the belief values for channels 2 and 3 to be, $p_{t,2} = 0.3$ and $p_{t,3} = 0.7$, respectively. At low values of $p_{t,1}$ (i.e., low belief that channel 1 is idle), the adaptive scheme assigns the highest priority frame (i.e., frame I) to channel 3 as it has the highest belief value. As $p_{t,1}$ increases, channel 1 becomes better in terms of availability. Hence, after $p_{t,1}^{*}$, the P and B frames are swapped to meet the deadline constraints. As $p_{t,1}$ continues to increase until it reaches $p_{t,1}^{**}$, the I frame is assigned to channel 1, while the P frame is assigned to channel 3.

To assess the performance of our adaptive assignment scheme, we plot the UE's utility, defined as the total probability of frames correct reception versus channel quality and belief values of channel 1 in Figures 5 and 6, respectively. We compare the performance of the proposed adaptive scheme against two benchmarks. The first benchmark is the average UE's utility, which is calculated from different permutations of assigning video frames to different channels. The second one is the worst case assignment. The priority ratio of the I, P, and B frames are $7:2:1$. In figure 5, the HeNB's belief vector is $\mathbf{p}_t = [0.2 \ \ 0.9 \ \ 0.3]$ and the BER values at channels 2 and 3 are $b_{t,2} = 10^{-7}$ and $b_{t,3} = 10^{-3}$, respectively. The proposed assignment scheme can enhance the UE's utility by $1.52x$ the average UE's utility and $2.45x$ the UE's utility under the worst case scenario. In figure 6, we set the BER values for all channels to be 10^{-3} and the HeNB's belief value for channels 2 and 3 to be, $p_{t,2} = 0.3$ and $p_{t,3} = 0.7$, respectively. Intuitively, as the belief of the HeNB that channel 1 is idle increases, the UE's utility increases, as the probability of correct reception of video frames increases. Using our adaptive scheme, the UE can achieve, under certain scenarios, a utility that is $1.65x$ the average UE's utility and $1.93x$ the UE's utility under the worst case scenario.

Figure 7 shows the UE's utility versus $p_{t,1}$ at different values of $p_{t,2}$. Due to space limit, the legend of figure 7 is $\square$: Adaptive ($p_{t,2} = 1$), $\diamond$: Mean ($p_{t,2} = 1$), $\triangle$: Minimum ($p_{t,2} = 1$), $+$: Adaptive ($p_{t,2} = 0.3$), o: Mean ($p_{t,2} = 0.3$), $*$: Minimum ($p_{t,2} = 0.3$). At each $p_{t,2}$ value, the proposed adaptive scheme returns higher utility for the UE compared to the average and minimum utilities. As $p_{t,2}$ increases, UE's utility increases as the probability of video frames' correct reception increases. This results could be interpreted in two different ways. First, $p_{t,2} = 1$ could be interpreted that channel 2 is a licensed channel, where the HeNB has exclusive right to use it. Second, for low dense unlicensed spectrum, the HeNB could have a very high belief that channel 2 is idle at this time instant. For both cases, the UE can achieve higher utility compared to the case where $p_{t,2} = 0.3$, as shown in Figure 7.

Figure 8 shows the UE's utility versus I frame weight. In this figure, we vary the I, P, and B frames' weight according to the following equation: $x : (2 \times (1-x))/3 : (1-x)/3$, where x takes values from 0.5 to 0.9. We set $\mathbf{p}_t = [0.3 \ \ 0.7 \ \ 0.9]$ and $\mathbf{b}_t = \left[10^{-2} \ \ 10^{-4} \ \ 10^{-7}\right]$. As the weight (equivalent to priority) of the I frame increases, the UE's utility enhancement, that results from the proposed adaptive scheme, increases. Hence, the proposed scheme works better (i.e., returns higher utility for the UE) when different video frames have very different deadlines (i.e., deadline variance is high).

V. Conclusions

Motivated by the increasing demand on wireless spectrum and the availability of more unlicensed spectrum in the 5

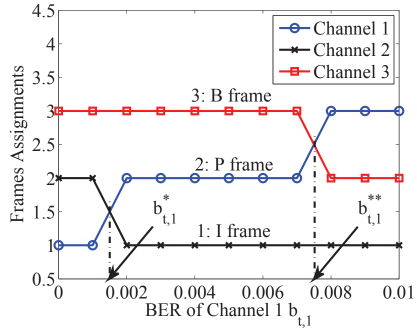

Fig. 3. Frames' assignment vs. channel 1 BER.

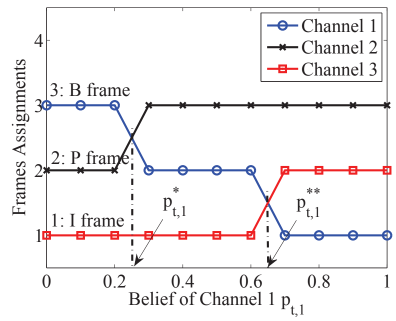

Fig. 4. Frames' assignment vs. channel 1 belief.

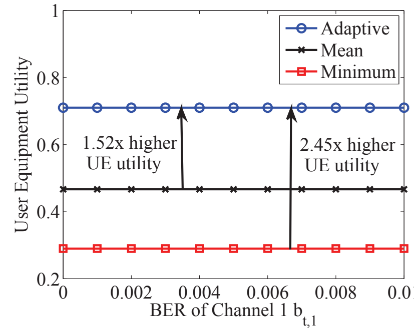

Fig. 5. UE's utility vs. channel 1 BER.

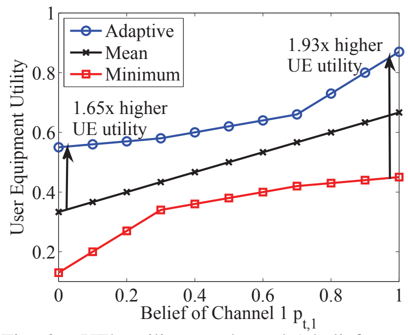

Fig. 6. UE's utility vs. channel 1 belief.

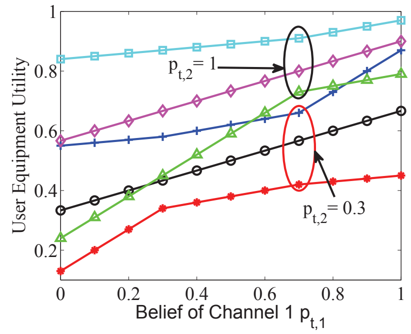

Fig. 7. UE's utility vs. channel 1 belief at different values of channel 2 belief.

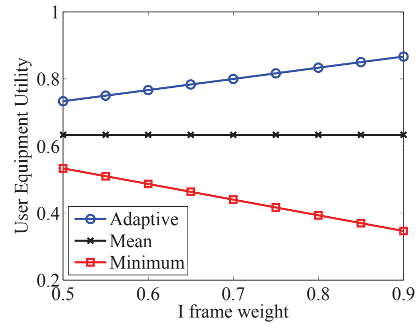

Fig. 8. UE's utility vs. I frame weight.

GHz band, it was recently proposed to enable the operation of LTE-A in the unlicensed 5 GHz band (so called, LTE-U) by aggregating licensed and unlicensed spectrum. Since the main motivation behind this approach is to satisfy throughput-hungry applications, we propose, in this paper, an adaptive channel assignment scheme for video frames to enable media streaming over LTE-U small cells. The objective of the proposed scheme is to optimally assign video frames to licensed and unlicensed channels according to Wi-Fi activity, channel quality, and different deadlines of the video frames (playback deadline, decoding deadline, and buffer underflow). From the numerical investigations, we found that the proposed adaptive scheme can enhance the UE's utility by around $2.45x$ when compared to traditional assignment schemes of video frames.

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