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JAGSRC: Joint Analysis Gain for short-range communication in Wireless Sensor Networks of 5G Wireless Communications

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Abstract:

In this paper, we look at the co-occasion issue between Wi-Fi and a pre-standard sort of LTE over unlicensed gatherings, particularly, LTE-Unlicensed (LTE-U). We address two simultaneousness issues. To begin with, the particular access instruments for Wi-Fi and LTE-U can provoke an extension of the effective rate and higher idleness for the two systems. We propose an adjusted Wi-Fi movement modeI, e Joint Analysis Gain for short-range communication (JAGSRC) whereby Wi-Fi stations (STAs) do simultaneous range distinguishing and transmission to decrease the time required for affect disclosure. Specifically, we propose and look at a full-duplex (FD) based disclosure framework that can isolate between Wi-Fi and LTE-U signals while thinking about remaining self-deterrent. Second, the ability to isolate between Wi-Fi and LTE-U signals rouses changing the sensible channel assessment (CCA) edge as demonstrated by the kind of the recognized banner. Animated by best in class Wi-Fi models (e.g., IEEE 802.11ax), we propose a JAGSRC restrain alteration design and concentrate by methods for generations it's optimal setting to grow the spatial reuse while keeping up tolerability between LTE-U and Wi-Fi structures. JAGSRC is to reduce error rate compared to existing methodology and it is also very accurate.

Keywords — Wi-Fi/LTE-U coexistence, full-duplex, simultaneous transmission-sensing, JAGSRC threshold adaptation.

I. INTRODUCTION

The normal WSN addition to remote demand in the region between 2010 and 2020, affected the LTE to open up parts of the 5 GHz band for unlicensed access. Given the closeness of this band to their approved range, remote chairmen ended up being extremely enlivened by growing the benefits of LTE-A to the unlicensed range (LTE-U). The rule thought behind LTE-U is to abuse the carrier amassing (CA) feature in LTE-A structures to join approved LTE 4G territory and unlicensed 5 GHz go, concentrating on higher downlink (DL) throughput for LTE customers. Simultaneousness between heterogeneous structures (e.g., LTE-U and Wi-Fi) in the unlicensed 5 GHz band is particularly trying a result of the qualification in the passage instrument used by the two systems. In particular, Wi-Fi structures are strife based however LTE/LTE-U systems are design based. Such heterogeneity may incite higher crash rate and idleness. With a true objective to diminish the LTE-U impacts over Wi-Fi system, two LTE approaches have been proposed: The timetable-based LTE-U [1] and the question-based LTE-U [2](e.g., approved got to (LAA)).

LTE-U gets the chance to extend in a period division multiplexing based frame (see Figure 1). LTE-U measures dynamic Wi-Fi transmission in the midst of the OFF period and alters its commitment cycle as requirements are. Since LTE-U is depended upon to be a start without a moment's hesitation approach in a couple of countries, for instance, US and China, in this paper, we base on the simultaneousness issue between Wi-Fi and LTE-U structures. In IEEE 802.11 standards, stations (STAs) battle using the enhanced appropriated channel get to (EDCA) contrive, which is an increase to the striking scattered coordination work (DCF). The viable STA can hold the channel for a length called a transmit opportunity (TXOP). In the midst of a TXOP, a Wi-Fi gets the opportunity to point (AP) or STA may exchange different of edges (see Figure 1). At the completion of the TXOP, the transmitting AP transmits a square ACK request (BAR) to the getting STA, which answers with a piece ACK (BA) hailing right assembling [3]. A TXOP may last up to 3.008ms. LTE-U execution may provoke genuine organization degradation for standard Wi-Fi customers, since the home eNodeB (HeNB) may start its transmission and effect AP transmission. As showed up in Figure 1, regular AP distinguishes the failure of its transmission after the BA times out realizing long deferments, diminished throughput, and influence incident for the two structures (e.g., plots F2 – F4 are lost, yet AP just considers it after TXOP closes). In this paper, we propose to furnish Wi-Fi STAs with self-check disguise (SIS) abilities to engage synchronous transmission and identifying (STS). This indicated full-duplex (FD) identifying outfits Wi-Fi device with more care about neighboring structures. If an LTE-U hail is identified, Wi-Fi device can back off earlier avoiding long delay as a result of effect or change to another sit channel. FD identifying was at that point researched for opportunistic dynamic range get to (DSA) systems using imperativeness [4, 5] and waveform-[6] based revelation. Essentialness area can't separate between sorts of different signs (e.g., LTE-U versus Wi-Fi). Given that Wi-Fi and LTE-U signals are both OFDM controlled, we will probably saddle their striking features to remember them. The makers in [7– 9] abused the cyclic prefix (CP) of OFDM pictures for the signal area, yet only for half-duplex (HD) structures (i.e., recognizing exactly where no extra hindrance exists). Makers in [10] proposed furnishing LTE contraptions with FD capacities to identify Wi-Fi signals using cycle stationarity yet did not discuss using their arrangement for improving the execution of other simultaneous systems.

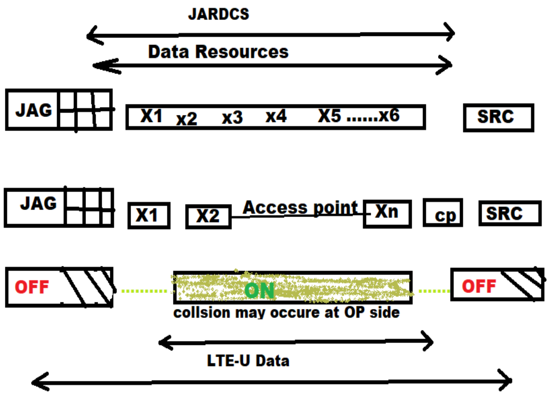

Fig. 1: Collision between LTE-U and JAGSRC Wi-Fi transmission frames structure.

The past composing, except for [7], require long recognizable proof time. In this paper, we propose and dismember an FD recognizing approach for existing together Wi-Fi/LTE-U structures in perspective of a two-sliding-window correlator plot, which has, for the most part, speedier ID time. In Wi-Fi structures, an STA contrasts the consider got signal quality and a sensible channel examination (CCA) edge before its transmission. Channel is thought to be possessed when assessed signal control outperforms CCA edge. Pending Wi-Fi standards (e.g., 802.11ax) expect to overhaul the spatial reuse by changing CCA restrain regard. In any case, the detail structure record (SFD) does not analyze how Wi-Fi STAs should react when an LTE-U hail is perceived. Isolating between LTE-U and Wi-Fi signals goads us to inspect the perfect CCA edge setting that enhances the spatial reuse while keeping up respectability between Wi-Fi and LTE-U structures. For example, decreasing as far as possible for Wi-Fi STAs will make Wi-Fi more preservationist and inclination the framework throughput towards LTE-U. On the other hand, extending this utmost will make Wi-Fi STAs more intense in getting to the range, which could be outlandish to the LTE-U system. We will probably alter the beforehand specified trade-off by choosing the perfect CCA to constrain regard. Past wears down LTE-U/Wi-Fi simultaneousness watched out for different issues, running from evaluating the execution of existing together systems through experimentation to separating it using stochastic geometry [13]. To the best of our knowledge, this is the essential paper to join FD frameworks to enhance Wi-Fi TXOP mode execution inside a Wi-Fi/LTEU simultaneousness structure and to discuss the perfect Wi-Fi CCA restrict setting with respect to LTE-U signals. The responsibilities of this paper are according to the accompanying. To begin with, we propose a changed TXOP contrive for Wi-Fi STAs with SIS capacities, which enhances go care and decreases the time required for effect distinguishing proof. We decide the probabilities of area and false-alarm under flawed SIS and propose a Nyman-Pearson (NP) revelation run the show. The proposed FD locator, overall, achieves 10–3 mis-ID probability at −6 dB LTE-U movement to-clatter extent. Second, to redesign the spatial reuse, we propose an adaptable CCA edge plot for Wi-Fi systems. We consider by methods for re-enactments the perfect CCA constrain an impetus for Wi-Fi STAs, which upgrades the sensibility of channel access for Wi-Fi and LTE-U little cells. Our examination reveals that the perfect CCA restrain is a part of two factors: LTE-U commitment cycle and LTE-U/Wi-Fi center point densities.

II. SYSTEM MODEL:

We consider an LTE-U little cell that matches with a Wi-Fi arrange in the 5 GHz unlicensed gatherings. The LTE-U little cell contains a HENB that talks with different UEs over an aggregate of approved and unlicensed channels. HENB must output for a free channel to use. If no sit out of rigging channel is found, HENB confers the range to the Wi-Fi system according to an adaptable commitment cycling (see LTE-U HENB development in Figure 1). Without loss of comprehensive explanation, we base on the LTE-U downlink.

The Wi-Fi system involves one FD enabled AP that talks with different STAs. Wi-Fi STAs (AP and non-AP) perform standard CSMA/CA before getting to any of the available unlicensed channels. The proposed TXOP undertaking mode is showed up in Figure 1 (see Full-duplex Wi-Fi AP development). The Wi-Fi AP performs simultaneous transmission and recognizing for a couple consecutive housings. For this situation, the AP recognizes an LTE-U signal while transmitting diagram F2. In perspective of the banner level of the distinguished LTE-U signal (analyzed in Section IV), the AP may back off until the point when the accompanying OFF period or change to another sit still channel. We expect that the LTE-U, Wi-Fi, and confusion signals at testing time n, implied by $l(n)$, $s(n)$, and $w(n)$, independently, take after a symmetric round complex Gaussian scattering: $l \sim \mathcal{N}c(0,\ \sigma2\ l\ )$, $s \sim \mathcal{N}c(0,\ \sigma2\ s\ )$, and $w \sim \mathcal{N}c(0,\ \sigma2\ w)$, independently. The check at the Enabled Wi-Fi contraption can be conveyed as takes after:

r(n)= $\beta2\sigma2\ \tilde{}l/\sigma2\ w$ ($\sigma2$ *l) +w(N) (1)

where $*$ is the convolution assignment, hlw is the channel get among HENB and the Wi-Fi AP (STA), and hww is basically the get of the impedance channel of Wi-Fi AP (the reducing between the transmit and get chain of the FD AP), and χw is the SIS limit of the Wi-Fi AP (perfect SIS occurs at $\chi w = 0$). We acknowledge an immediate channel appear, and consequently channel, yields will remain conventionally scattered. We revolve around the recognizing LTE-U signals at a Wi-Fi centre. We display three estimations: the LTE-U deterrent to-upheaval extent (INR) $\sigma2\ l/\sigma2\ w$, which assesses the extent of LTE-U signal level with respect to the vitality of Wi-Fi racket floor, the bury picture impedance (ISI) ISI-to-uproar extent (ISNR) $\beta2\sigma2\ \tilde{}l/\sigma2\ w$ ($\sigma2\ \tilde{}l$ is the vitality of past got LTE-U picture, β models ISI). ISNR assesses the sum ISI that LTE-U hail perseveres concerning the vitality of Wi-Fi tumult floor, and the self-impediment to-fuss extent (STNR) $\chi2\ w\sigma2\ s/\sigma2\ w$, which measures the Wi-Fi extra self-impedance (RSI) control level with respect to that of Wi-Fi commotion floor.

III. CYCLIC-PREFIX-BASED DETECTION

LTE-U and Wi-Fi signals are OFDM modulated, where each OFDM symbol consists of a data part and a pre-appended CP (see Figure 2). CP is a replication of some data symbols, and it is added to mitigate the ISI and facilitate synchronization at receivers. CP is most likely to be contaminated by ISI. Consider an LTE-U signal with OFDM symbol structure consisting of N data and L CP samples. At the Wi-Fi receiver, the received analog signal is passed through the analog-to-digital (ADC) converter to obtain discrete samples. Later on, these samples are partitioned into two windows, $W1$ and $W2$, of length L and a timing difference equals $N - L$. We slide these two windows structures over all received samples (see Figure 2). We call the time instant for which window $W1$ aligns with LTE-U's samples corresponding to CP the optimal time, and other times as regular times. We correlate samples in these windows using a timing metric that will be presented shortly and compare correlation value with a predefined threshold. At the optimal time, the correlation exceeds the threshold and a presence of an LTE-U signal is indicated, while at regular times the correlation value will be lower than the threshold. We propose the following correlation timing metric:

$M\tau\ (n) = |A(n)|\ 2\ (\max\ (E1(n),\ E2(n)))2$ 2

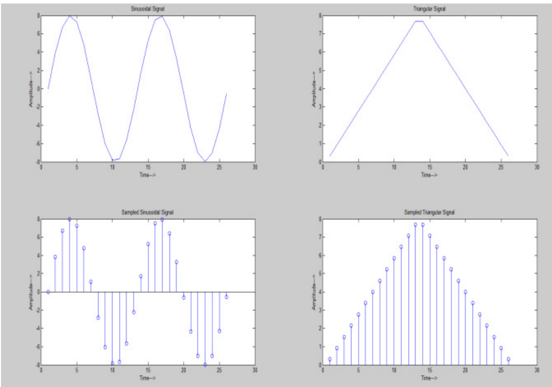

Fig. 2: Sliding-window-based OFDM signal detector.

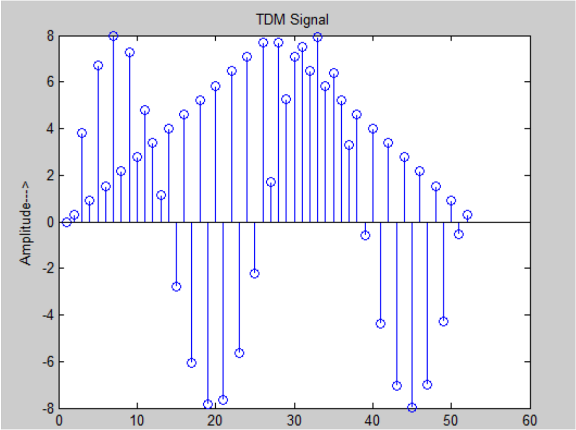

Fig. 3: $M\tau\ (n)$ vs. $n/(N + L)$.

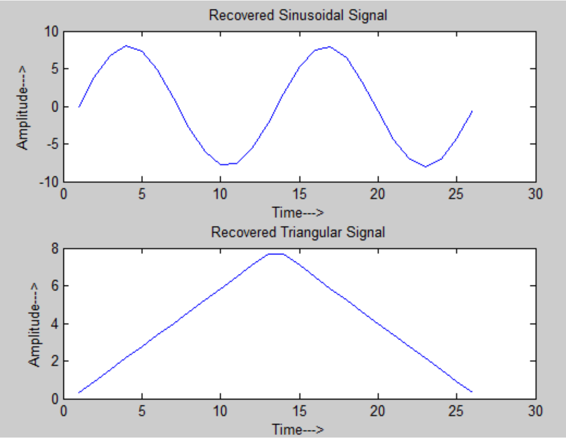

Fig. 4: $M\tau\ (n)$ vs. $\tau/(N + L)$.

where $A(n)$ is the correlation between samples in the two windows, and $E1(n)$ and $E2(n)$ are the energies of the samples in the two windows, respectively:

$A(n) = \Sigma L{-}1\ k{=}0\ r\ (n - k)\ r{*}\ (n - k - N)$ (3)

$E1(n) = \Sigma L{-}1\ k{=}0\ r(n{-}k{-}N)\ r{*}(n{-}k{-}N)$

$E2(n) = \Sigma L{-}1\ k{=}0\ r(n{-}k)\ r{*}(n{-}k)$

where $r{*}$ indicates the complex conjugate of r. The τ index in $M\tau$ indicates the alignment of the sliding windows with respect to the starting point of the OFDM symbol (i.e, CP). τ takes integer values in the period $(-(N + L)/2,\ (N + L)/2]$, with $\tau = 0$ corresponding to the optimal time, while $\tau{>}L$ corresponds to regular times. Figure 3 shows $M\tau\ (n)$ as a function of the OFDM symbol index, when four symbols are detected. Figure 4 depicts $M\tau\ (n)$ as a function of misalignment index τ . Both figures are generated with INR = 25 dB, L = 500, N = 6400, and ISNR = 6 db. The hypothesis testing can be defined as follows:

$r(n){=}\ ws(n) + w(n)$, under $\mathcal{H}0$

$l(n){+}\chi ws(n){+}w(n)$, under $\mathcal{H}0$, n is a regular time

$l(n){+}\chi ws(n){+}w(n)$, under $\mathcal{H}1$, n is the optimal time

where the first two lines represent the null hypothesis $\mathcal{H}0$, and the third line represents the alternate hypothesis $\mathcal{H}1$. Define the general detection rule as:

$\delta(r(n)) =$ 1, if $M\tau\ (n) \geq \lambda th$

0, if $M\tau\ (n) < \lambda th.$ (4)

Before proposing the NP rule that selects the threshold λth, we first derive $M\tau\ (n)$ statistics under different hypotheses.

A. Statistics at the Optimal Time

According to (1), at $\tau = 0$, the received samples in the two-sliding-window at Wi-Fi AP receiver are:

$r(k{-}N) = \beta\tilde{\ }l(k{-}N) + l(k{-}N) + \chi ws(k{-}N) + w(k{-}N)\ r(k) = l(k) + \chi ws(k) + w(k)$ (5)

where $k\in \{n - L + 1, \cdots, n\}$, $r(k{-}N)$ and $r(k)$ represent the samples in the first and second windows, respectively, and $\tilde{\ }l$ denotes samples from the previously transmitted OFDM symbol that overlap with the current received OFDM symbol due to ISI. We drop the channel dependence in (1), since the channel will not change the distribution of the transmitted samples. $l(k{-}N)$ in (5) belongs to the CP, while $l(k)$ belongs to CP's original duplicated part, and both have equal magnitude.$l\ (k\ {-}N)$ and $\tilde{\ }l\ (k\ {-}N)$ are independent since they belong to two different LTE OFDM symbols. We assume the noise samples to be independent and identically distributed, so $w(k - N)$ and $w(k)$ are also independent. For coloured noise, pre-whiting techniques can be applied. $A(n)$ in (3) can be written as $A(n) = \sum nk{=}n{-}L{+}1\ Ak$, and accordingly the mean $\mu Ak = E[Ak] = \sigma 2\ l$ and the variance $\sigma 2\ Ak$ is evaluated as:

$\sigma 2\ Ak = 3\sigma 4\ l + \sigma 4\ w + \chi 4\ w\sigma 4\ s + \beta 2\sigma 2\ \tilde{\ }l\sigma 2\ l + \beta 2\sigma 2\ \tilde{\ }l\sigma 2\ w + \chi 2\ w\beta 2\sigma 2\ \tilde{\ }l\sigma 2\ s + 2\sigma 2\ l\sigma 2\ w + 2\chi 2\ w\sigma 2\ s\sigma 2\ l + 2\chi 2\ w\sigma 2\ s\sigma 2\ w - \mu 2\ Ak.$ (6)

By the central limit theorem (CLT), for large L, $A(n)$ will be normally distributed with mean of $\mu A = L\mu Ak$ and variance $\sigma 2\ A = L\sigma 2\ Ak$. In practice, at the optimal time, $A(n)$ will be composed of a dominant real part and a small imaginary part. The statistics and distribution for the denominator in (2) can be derived by finding the mean and variance of $E1$ and $E2$. It is straightforward to show that $E1$ and $E2$ are normally distributed $E1 \sim\mathcal{N}\ (L\mu E1{,}k,\ L\sigma 2\ E1{,}k)$, $E2 \sim\mathcal{N}\ (L\mu E2{,}k,\ L\sigma 2\ E2{,}k)$, where the mean $\mu E2{,}k = \sigma 2\ l + \chi 2\ w\sigma 2\ s + \sigma 2\ w$, variance $\sigma 2\ E2{,}k = 2\mu 2\ E2{,}k$, $\mu E1{,}k = \beta 2\sigma 2\ \tilde{\ }l + \mu E2{,}k$, and $\sigma 2\ E1{,}k = 2\mu 2\ E1{,}k$. For low ISI conditions (e.g., ISNR $\leq$ INR), $E1$ and $E2$ have almost similar statistics, and accordingly $Z(n) \triangleq \max\ (E1(n),\ E2(n))$ is normally distributed, $Z{\sim}\mathcal{N}\ (\mu z,\ \sigma 2\ z\ )$, where the mean μz and the variance $\sigma 2\ z = \mathrm{E}[Z2] - \mu 2\ z$ are derived as in [14]:

$\mu z = \mu E1\Phi(\eta) + \mu E2\Phi(-\eta) + \theta 12\phi(\eta)\ \mathrm{E}\ [Z2]{=}(\sigma 2\ E1 + \mu 2\ E1)\Phi(\eta){+}(\sigma 2\ E2 + \mu 2\ E2)\Phi(-\eta) + (\mu E1 + \mu E2)\theta 12\phi(\eta)$
(7)

where $\Phi(\cdot)$ and $\phi(\cdot)$ are the CDF and PDF of the standard normal function, $\eta = (\mu E1 - \mu E2)/\theta 12 = \beta 2\sigma 2\ \tilde{\ }lL/\theta 12$, and $\theta 12 = \surd\sigma 2\ E1 + \sigma 2\ E2 - 2\rho 12\sigma E1\sigma E2$. The correlation coefficient $\rho 12$ represents the correlation index between $E1$ and $E2$, $\rho 12 = (\mathrm{E}\ [E1E2] - \mu E1\mu E2)/(\sigma E1\sigma E2)$. Let $b = \sigma 4\ w + \chi 4\ w\sigma 4\ w + \beta 2\sigma 2\ \tilde{\ }l\sigma 2\ l + \beta 2\sigma 2\ \tilde{\ }l\sigma 2\ w + \chi 2\ w\beta 2\sigma 2\ \tilde{\ }l\sigma 2\ s + 2\sigma 2\ l\sigma 2\ w + 2\chi 2\ w\sigma 2\ l\sigma 2\ s + 2\chi 2\ w\sigma 2\ w\sigma 2\ s$, then $\mathrm{E}\ [E1E2] = L(3\sigma 4\ l + b){+}(L2 - L)(\sigma 4\ l + b)$. Let $Q(n) \triangleq A(n)/Z(n)$. Then, $Q(n)$ is the ratio of two normal random variables. For small standard deviation to mean ratios for $A(n)$ and $Z(n)$, $Q(n)$ has approximately a normal distribution, $Q(n) \sim\mathcal{N}\ (\mu Q,\ \sigma 2\ Q)$ [15], where the mean μQ, and the variance $\sigma 2$

Q can be approximated with the help of Taylor series as in [16]:

$\mu Q = \mathrm{E}[AZ] \approx \mu A \mu Z + \mathrm{Var}\,(Z)\, \mu A \mu 3\, Z - \mathrm{Cov}\,(AZ)\, \mu 2$

$\sigma 2\, Q \approx (\mathrm{Var}\,(A)\, \mu 2\, Z + \mu 2\, A \mathrm{Var}\,(Z)\, \mu 4\, Z - 2 \mu A \mathrm{Cov}\,(AZ)\, \mu 3\, Z)$

where $\mathrm{Cov}\,(AZ) = \mathrm{E}[AZ] - \mu A \mu Z$ is the covariance between A and Z, and $\mathrm{E}\,[AZ]$ can be evaluated as follows: $\mathrm{E}\,[AZ] = \mathrm{E}[AE1]\ \Pr\,[E1 > E2] + \mathrm{E}[AE2]\ \Pr\,[E2 > E1]$. We found through simulations that, on average, $\Pr\,[E1 > E2] \approx 1$ when LTE-U signal level with respect to ISI satisfies INR − STNR ≤ 15 dB. Let $c = \sigma 4\, l + \sigma 2\, l \sigma 2\, w + \chi 2\, w \sigma 2\, w \sigma 2\, s$, then $\mathrm{E}\,[AE1] = 3L(c + \beta 2 \sigma 2\, \tilde{}l \sigma 2\, l) + (L2 - L)(c + \beta 2 \sigma 2\, \tilde{}l \sigma 2\, l)$ and $\mathrm{E}\,[AE2] = 3Lc + c(L2 - L)$. The last step is to evaluate the distribution of $M\tau{=}0(n) \triangleq |Q(n)|\ 2$, which is the square of a normal random variable.

$M\tau{=}0$ has a chi-square distribution; however, for small $Q(n)$'s variance-to-mean ratio, $M\tau{=}0$ can be approximated as a normal random variable [17]:

$M\tau{=}0 \sim (\mu Q + N(0, \sigma 2\, Q))2 \approx \mu 2\, Q + 2 \mu q N(0, \sigma 2\, Q)$

with mean $\mu M\tau{=}0 = \mu 2\, Q$, and variance $\sigma 2\, M\tau{=}0 = 4 \mu 2\, Q \sigma 2\, Q$. The probability of detection for a threshold λth is:

$\mathrm{Pd}\,(\lambda th) = \Pr\,[\{M\tau{=}0 \geq \lambda th | \mathcal{H}1\}] = \mathcal{Q}\,(\lambda th - \mu M\tau{=}0\ \sigma M\tau{=}0)$ (8)

where $\mathcal{Q}(\cdot)$ is the complementary cumulative function of the standard normal distribution.

B. Statistics at Regular Times

At regular times, the samples in the two-sliding-window are formulated as in (5) by dropping the $\beta \tilde{}l(k{-}N)$ term. $r(k)$ and $r(k - N)$ are independent samples. The correlation process in (3) results in summing complex random samples, and for large L, by CLT, $A(n)$ will be composed of real and imaginary parts that are independent and normally distributed. The mean and variance of $A(n)$'s real and imaginary parts can be derived in a similar way we did in (6), and they will have a zero mean and a variance of $L(\sigma 2\, l + \sigma 2\, w + \chi 2\, w \sigma 2\, s)2/2 = L \mu 2\, E2,k/2$. $|A(n)|\ 2$ is the sum of the squares of two normal random variables, and hence $|A(n)|\ 2$ will be chi-square distributed, and with an appropriate scaling it will be:

$|A(n)|\ 2 \sim L(\mu E2,k)\ 2 \mathcal{X}\ 2\ 2$ (9)

where $\mathcal{X}\ 2\ 2$ is the chi-square distribution. $Z(n)$ has a normal distribution $Z \sim \mathcal{N}\,(\mu Z, \sigma 2\, Z)$. The mean and variance of $E1(n)$, $E2(n)$, and $Z(n)$ can be derived in a similar way as we did before at the optimal time in (7), except the fact that the correlation coefficient $\rho 12$ is zero. These entities remain normally distributed, and their statistics are $\mu E1 = \mu E2 = L \mu E2,k$, $\sigma 2\, E1 = \sigma 2\, E2 = 2L \mu 2\, E2$, $\mu z = (L + 0.7978 \surd\ L) \mu E2$, and $\sigma 2\, Z = (L2 + 3.128L) \mu 2\, E2$. $Z2(n)$ is the square of a normal random variable and has chi-square distribution. $Z2(n)$ can be approximated with a normal distribution [17]:

$Z2 \sim (\mu Z + \mathcal{N}\,(0, \sigma 2\, Z))2 = \mu 2\, Z + 2 \mu Z \mathcal{N}(0, \sigma 2\, Z) + (\mathcal{N}\,(0, \sigma 2\, Z))2 \approx \mathcal{N}\,(\mu 2\, Z, 4 \mu 2\, Z \sigma 2\, Z)$. (10)

The timing metric at the regular time $M\tau{>}L$ is the ratio of the distributions in (9) and (10):

$M\tau{>}L \sim L \mu 2\, E2\ \mathcal{X}\ 2\ 2\ \mathcal{N}\,(\mu 2\, Z, 4 \mu 2\, Z \sigma 2\, Z) \approx L \mu 2\, E2\ \mu 2\, Z\ [\,\mathcal{X}\ 2\ 2 - \mathcal{N}\,(0, 4\, \sigma 2\, Z \mu 2\, Z)\,] \approx a1 \mathcal{X}\ 2\ 2$ (11)

where $a1 = L/(L + 0.7978 \surd\ L)2$. We handle the previous approximations in a similar way to the analysis in [17]. The scaling in (11) results in a gamma distribution $\Gamma(\,k\ 2\ , 2a1)$ with a shape parameter of $k/2{=}1$ and a scaling parameter of $2a1$. As seen in (11) $M\tau{>}L$ has a gamma distribution that is independent of the noise or signal statistical properties, $M\tau{>}L$ distribution is only dependent on L, which depends on the length of CP for LTE-U signals and the sampling frequency of Wi-Fi AP. False alarm probability for a detection threshold λth can be can be formulated according to the CDF of gamma distribution

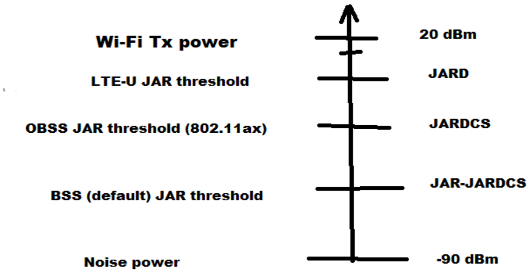

Fig 5: Illustration of the proposed JAG adaption scheme for Wi-Fi system.

$F\gamma,1,2a1\ (\cdot)$ that has a shape parameter equals one and scale parameter equals to $2a1$: $PF\,(\lambda th) = \Pr[\{M(\tau{>}L) > \lambda th\} | \mathcal{H}0] = 1 - F\gamma,1,2a1\ (\lambda th)$. (12)

C. Statistics in the Absence of OFDM Signal

In the absence of OFDM signal, we denote the timing metric by Mu. The samples in the two-sliding-window are formulated as in (5) by dropping $\beta \tilde{}l(k - N)$, $l(k)$, and $l(k - N)$ terms. Mu's distribution and statistics can be derived in a similar manner as we did for the regular time:

$Mu \sim L(\sigma 2\, w + \chi 2\, w \sigma 2\, s)2\ \mu 2\, Z \mathcal{X}\ 2\ 2 = L\,(L + 0.7978 \surd\ L)2\ \mathcal{X}\ 2\ 2$ (13)

where $\mu z = \mu E1 + 0.3989 \surd 2 \sigma E1$, $\mu E1 = L(\sigma 2\, w + \chi 2\, w \sigma 2\, s)$, and $\sigma 2\, E1 = 2L(\sigma 2\, w + \chi 2\, w \sigma 2\, s)2$. Mu has a gamma distribution similar to the one derived before in (11), and hence it has a similar probability of false alarm as in (12).

D. NP Detection

We propose an NP detection rule based on the previously derived statistics. There are two sources of false alarms, the first happens when there is no LTE-U signal, while the second occurs at the regular time. Given the distributions in (11) and (13), then the NP detection threshold $\lambda th = \lambda NP$ in (4) is:

$$\lambda th = \lambda NP = F -1\ \gamma,1,2a1\ (1 - \alpha). \qquad (14)$$

where α is the maximum false-alarm probability. The NP detector does not require any prior knowledge about neither signal nor noise statistical characteristics; it only requires the knowledge about the CP length (i.e., L).

Algorithm 1: AdaptiveJAGSRC Algorithm

```
for each Wi-Fi STA that wants to transmit do
    Wi-Fi STA executes JAG (sense for SRC) using energy detection
    if RSSI $\leq \gamma BSS \approx -82$ dBm then
        Transmit
    else
        Wi-Fi JAG executes the LTE-U sliding window correlator
        if correlation metric: $M > \lambda th$ (i.e., LTE-U exists) then
            if RSSI $< \gamma LTEU$ dBm then
                Transmit
            else
                Back off (or switch to a new channel)
            endif
        else (correlation metric: $M \leq \lambda th$)
            Check the JAGcolor bits
            if JAG color bits indicates JAGSRC signal then
                if JAG $< \gamma$ JAGSRC dBm then
                    Transmit
                else
                    Back off (or switch to a new channel)
                end if
            else (e.g., JAGSRC color bits indicates JAG signal)
                Back off (or switch to a new channel)
            end if
        end if
    end if
end for
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V. PERFORMANCE EVALUATION

We consider a full-duplex enabled Wi-Fi STA with noise floor $\sigma 2\ w = -90$ dBm, and transmitted power $\sigma 2\ s = 20$ dBm. We set $\sigma 2\ \tilde{}l = \sigma 2\ w$ and vary $\sigma 2\ l$,β, and χw. We analyse how different SIS capabilities, and ISI contamination in the CP affect detector's performance for various setups using numerical and simulation results. We set $L = 500$ and $N = 6400$ taking into account the sampling frequency used in typical Wi-Fi receivers $fs \geq 20$ MHz and the time length of an LTE-U OFDM symbol (e.g., 72μsec). Unless otherwise stated, all simulation results were generated with 3000 realizations. Our objective is to evaluate the trade off between spatial reuse and Wi-Fi/LTE-U fairness by optimizing Wi-Fi CCA threshold. The simulation setup is as follows. We consider a square area of 200 × 200 square meters, with multiple Wi-Fi and LTE-U devices distributed according to a Poisson point process (PPP). Specifically, we randomly distribute the receivers (e.g., Wi-Fi STAs and UEs) in the specified area according to the PPP with parameter λPPP ($\lambda PPP \in [4, 80]$ is a simulation parameter). For a network with N receivers, the number of Wi-Fi STAs equals to the number of UEs. For each receiver, we assign a single transmitter (AP in case of Wi-Fi and HeNB in case of LTE-U) that is uniformly distributed in a square, of length 20 meters, around its corresponding receiver. All HeNBs have a duty cycle (DC), which we vary as a simulation parameter $\in [0.1, 0.9]$.

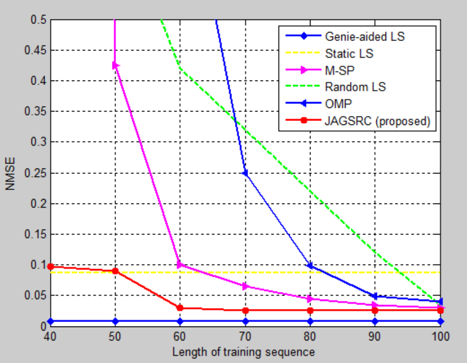

Fig. 6: Mis-detection probability vs. INR for various ISI levels ($PF = 0.01$, no RSI).

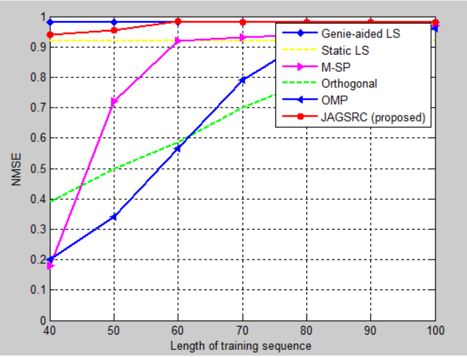

Fig. 7: Mis-detection probability vs. INR for various RSI levels (PF=0.01, ISNR=2 dB).

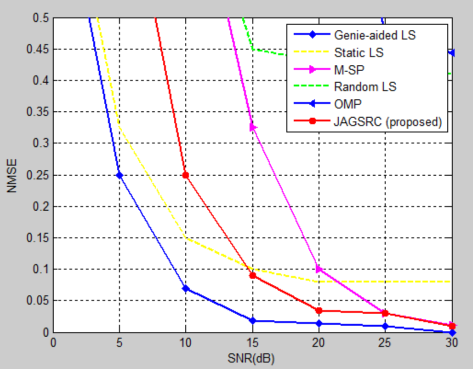

Fig. 8: ROC curves for various INR levels (ISNR = 2 dB, STNR = 5 dB).

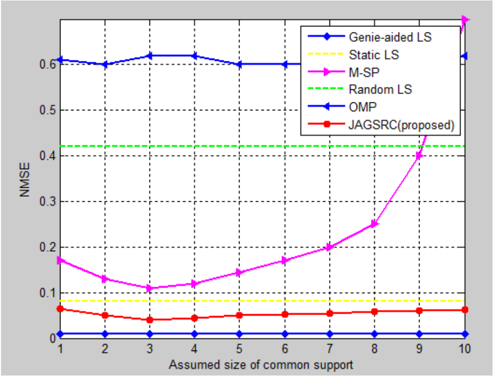

Fig. 9: Throughput vs. λJAG (DC= 0.5).

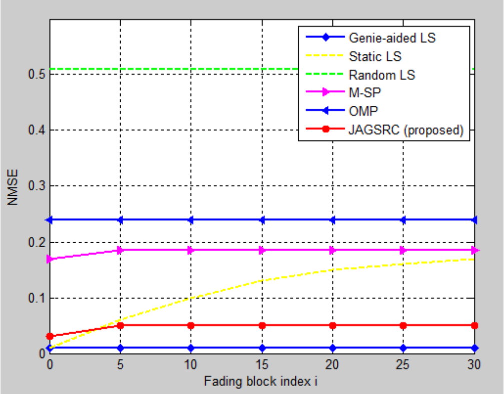

Fig. 10: Optimal CCA threshold vs. λJAG.

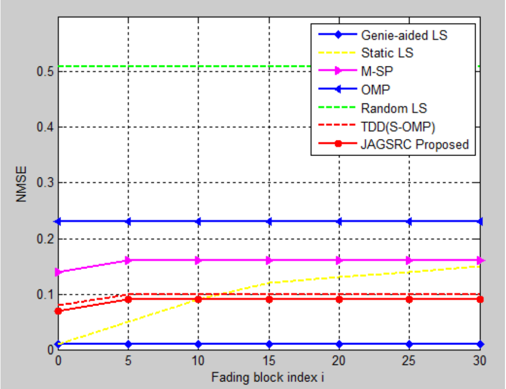

Fig. 11: Fair sum throughput vs. λJAG.

greediness in using the spectrum. Both CCA threshold values result in unfairness between the two technologies. Figure 10 shows the optimal values for γLTEU at different (λPPP) and at different DC values for the LTE-U systems. For each λPPP and DC values, our objective is to optimize γLTEU that minimizes the difference between the sum throughput of Wi-Fi and LTE-U systems (i.e., ensure fairness). Figure 11 shows the optimal sum throughput for both systems. We notice that as the LTE-U DC decreases, γLTEU decreases since Wi-Fi system is trying to ensure fairness with LTE-U systems. This behaviour continues until a certain threshold for the DC of LTEU systems, where the Wi-Fi systems cannot achieve fairness since the ON period of LTE-U small cells is very small. As shown in Figure 11, Wi-Fi and LTE-U systems achieve almost the same throughput $\forall\gamma$LTEU and DC except for very low DC values since the ON period for LTE-U systems is very short.

VI. CONCLUSIONS

Traditional JAGSRC mode in Wi-Fi systems may introduce latency and reduced throughput in case of Wi-Fi/LTE-U coexistence. In this paper, we proposed a modified JAGSRCmode, in which Wi-Fi STAs carry out simultaneous transmission and sensing by exploiting SIS techniques. We proposed and analyzed a sliding-window correlator detection framework under imperfect SIS and ISI that enables Wi-Fi to distinguish LTEU signals. We proposed an adaptive CCA threshold scheme that is based on the detected signal type. We optimized, via simulations, the CCA threshold value that maximizes the spatial reuse while maintaining a certain fairness degree between Wi-Fi and LTE-U. The proposed JAGSRC analysis better experimental results came compared to existing technology.

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