Response to the Reviewers' comments on "Sensing-Throughput Tradeoff for Interweave Cognitive Radio System: A Deployment-Centric Viewpoint (TW-Aug-15-1167)"

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Dear Editor,

We wish to thank you for your assistance in the review process which has helped us improve our manuscript significantly. We have revised our manuscript addressing all the valuable comments provided by the reviewers. We have highlighted (with blue color) the major changes in the revised paper. The main revisions are described below.

1) We have revised the introduction section in order to enhance its brevity and clarity, and to emphasize the main contributions of the paper.
2) To further enhance the novelty of the proposed approach in Section III, we have relaxed Assumptions 2, 5 and 6 of the previous manuscript in the revised manuscript. To highlight the main aspects covered by proposed approach, we have structured Section III into subsections, namely problem description (Section III-A), proposed approach (Section III-B), validation of the estimates (Section III-C), and assumptions and approximations (Section III-D).
3) In Section III-C of the revised manuscript, we have addressed a major concern regarding the knowledge of the presence of primary user ($\mathcal{H}_1$) that ensures the validity of the estimated parameters (refer Assumptions 5 and 6 of the previous manuscript), particularly for the sensing and the interference channels. To this end, we have proposed a novel methodology that utilizes the time resources within the frame duration efficiently without compromising the complexity of the channel estimation.
4) Previously, we considered the estimation and sensing as two disjoint events, refer Assumption 2 in the previous manuscript. However, in the revised manuscript, we have relaxed this assumption by combining the samples obtained from estimation and sensing phases, in this way, we further enhance the performance of our proposed approach in terms of sensing-throughput tradeoff. To complement this change in the analysis, we have modified Figures 2, 5, 6, 7, 8, 9 and 10 of the

revised manuscript.

5) In the revised manuscript, we have introduced an alternative approach that translates the variation introduced due to channel estimation to the optimum sensing time, refer Corollary 1 in Section IV. Moreover, the comparison in terms of performance of the mentioned approach to the original approach (depicted in Theorem 1 and 2) is highlighted (under Corollary 1) in Figures 9 and 10, refer Section IV of the revised manuscript.
6) In order to provide more insights into the estimation-sensing-throughput tradeoff depicted by the proposed approach, we have included Figure 8 in correspondence to the average constraint and the outage constraint in Section V of the revised manuscript.
7) We have moved the proofs of Lemma 3, Theorem 1 and Theorem 2 to the Appendix in the revised manuscripts.
8) In order to improve the presentation style, we have revised the whole manuscript carefully to avoid any typos and confusing statements.

In the following paragraphs, we respond to the reviewers' comments point by point.

Dear Reviewer 1,

Thank you very much for appreciating our work, and providing your valuable suggestions and insightful comments on our manuscript. The detailed revisions are listed in the following points.

Comment 1: *In the current work in Section III, the channel estimation is performed for hp1 and hp2 using a conventional method. However, channel estimation for spectrum sensing is actually more complicated than this. The problem with channel estimation in this case is that SU does not know whether PU is present or not. So there is a chance that SU is actually using samples without any channel gains for estimation. In the literature, the problem was first dealt with by using an iteration between estimation and sensing, that is sensing is performed and if the decision is that PU is present then estimation is performed etc. See [R1]. This problem can also be dealt with by using a kind of noncoherent estimation. See [R2]. I suggest that the authors replace their estimators with these in the paper.*

R1. V. Gautham Chavali and Claudio R.C.M. da Silva, "Collaborative spectrum sensing based on a New SNR estimation and energy combining method," IEEE Trans. on Vehicular Technology, vol. 60, no. 8, Oct. 2011.

R2. N. Cao, M. Mao, Y. Chen, "Analysis of collaborative spectrum sensing with BPSK signal power

estimation errors," IET-Science, Measurement & Technology, vol. 8, pp. 350 -358, Nov. 2014.

Author's Response: Thank you very much for pointing this out, we agree with the reviewer's concern regarding the fact the channel estimates will be valid only under situations when the primary user signal $(\mathcal{H}_1)$ is present, particularly for the sensing and the interference channels. We have addressed this concern in Section III-C of the revised manuscript. In comparison to [illegible]. and R2., we have proposed a differently methodology, according to which, we mention that, "we apply a coarse detection[1] on the estimates $\hat{P}_{\text{Rx,ST}}$, $\hat{P}_{\text{Rx,SR}}$ at the end of the estimation phase τ_{est}. Through an appropriate selection of the time interval interval τ_{est} ~~(for instance, $\tau_{\text{est}} \in [1, 10]$ ms)~~ at the system design, the reliability of the coarse detection can be ensured. With the existence of a separate control channel such as cognitive pilot channel, the reliability of the coarse detection can be further enhanced by exchanging the detection results among the ST and the SR.

Since the estimation and the coarse detection process are equivalent in terms of the mathematical operations used for their computation, we assure the validity of the [illegible]timates without trading against the complexity of the estimators employed by the secondary system. Moreover, by performing a joint estimation and (coarse) detection, we propose an efficient way of utilizing the time resources within the frame duration. The ST considers these estimates to determine a suitable sensing time based on the sensing-throughput tradeoff such that the desired detector's performance is ensured. At the end of [illegible]tection phase, we conduct a fine detection[2] of the PU signals [illegible]reby improving the performance of the detector."

Concerning the second part of the reviewer's comment, ~~which states,~~ *I suggest that the authors replace their estimators with these in the paper.* we have further emphasized in contribution 1 of the introduction section and the Section III-B of the revised manuscript that the estimation methods are proposed such that they deliver a decent tradeoff between reliability complexity and versatility (to a larger range of primary systems) of the proposed framework, as a result, facilitates the hardware realizability of the proposed framework. In this regard, we have proposed a received power estimation for the sensing and the interference channels.

Comment 2: *Another major concern is the optimization problem. At the moment, the authors found the average Pd, C0, C1 etc. and then perform optimization to remove estimation error variations. What about find the optimal tau from the original optimization problem and then average the optimal tau over*

[1]For the coarse detection, an energy detection is employed whose threshold is determined by means of a constant false alarm rate.
[2]In accordance with the proposed frame structure in Fig. 2, fine detection includes the samples acquired during in the estimation phase.

channel estimation error distributions? This may give some simple expression or an alternative to the authors' scheme.

Author's Response: Thank you for proposing this optimization approach alternative to the one considered in the paper. We have considered this approach in Corollary 1 in Section IV of the revised manuscript. According to which, we capture the variations due to imperfect channel knowledge in terms of the suitable sensing time subject to average and outage constraints. Subsequently, we determine the average throughput that capture variations in the parameters $\mathrm{C}_0, \mathrm{C}_1, \mathrm{P}_\mathrm{d}$ and $\tilde{\tau}_{\mathrm{sen}}$ (suitable sensing time) ~~based on this alternative approach~~. In order to address the analytical tractability of the mentioned approach ~~as stated~~ in Remark 2, ~~where~~ we mention, "Complementing the analysis in [13], it is complicated to obtain a closed-form expression of $\tilde{\tau}_{\mathrm{sen}}$ thereby rendering the analytical tractability of its distribution function difficult. In this view, we capture the performance of the alternative approach by means of simulations." In addition to that, the performance of the mentioned approach is compared to the original approach (illustrated in Theorems 1 and 2) in Figures 9 and 10 of the revised manuscript.

Comment 3: *It will also be nice if some of the proofs are moved to an appendix to improve presentation.*

Author's Response: To address this concern, we have moved the proofs of Lemma 3, Theorem 1 and Theorem 2 to the Appendix in the revised manuscripts~~.~~.

Comment 4: *subsections could be numbered.*

Author's Response: We have addressed this concern in the revised manuscript.

Comment 5: *It is not clear in (1) whether the channel is Gaussian or the transmitted signal is Gaussian.*

Author's Response: We have rephrased this statement in the Section II-B of the revised manuscript, where we mention, "the signal $x_{\mathrm{PT}}[n]$ transmitted by the PUs can be modelled as: (i) phase shift keying modulated signal, or (ii) Gaussian signal", refer Section II-B.

We would be very happy to address if you have any future comments in our manuscript.

Dear Reviewer 2,

Thank you very much for providing valuable suggestions ~~which have helped us improve our manuscript significantly~~. We have carried out a major revision on the manuscript guided by these valuable comments. The detailed corrections are listed in the following points.

Major Comment 1: *In many parts, the presentation of this paper is not formal. Thus, the language needs to substantially revised.* .

Author's Response: We have addressed this concern in the revised manuscript. In this regard, we have replaced several informal sentences with their formal versions, for instance:

1) "Due to its static allocation, this spectrum is on the verge of depletion." in paragraph 2 of the introduction section is replaced with "Due to its static allocation, this spectrum is on the verge of scarcity" in the revised manuscript.
2) "Over the past one and a half decade, this notion has evolved at a tremendous pace right from its origin by Mitola *et al.* in 1999 [4] and consequently, it has acquired certain maturity." in paragraph 3 of the introduction section is replaced with "Since its origin by Mitola *et al.* in 1999, this notion has evolved at a significant pace, and consequently has acquired certain maturity." in the revised manuscript.
3) "As a result, sustaining a target detection probability is of paramount importance to the ISs [13]." in paragraph 2 of the Section I-A is replaced with "As a result, the ISs have to ensure that they operate above a target detection probability [12]." in the revised manuscript.

Furthermore, we have revised the whole manuscript carefully to: (i) improve the presentation style, (ii) avoid typos and confusing statements.

Major Comment 2: *The sections "System Model" and "Proposed Model" are also confusing. What is the difference between the two sections?* .

Author's Response: Thank you for raising this concern. In addition to that, we have restructured Section III to highlight the main aspects covered by proposed approach, namely problem description (Section III-A), proposed approach (Section III-B), validation of the estimates (Section III-C), and assumptions and approximations (Section III-D) in the revised manuscript. In Section III-A, we have stated major issues encountered in the existing models supported by their mathematical formulations, and subsequently the methodology proposed for resolving these issues in Section III-B. In order to further enhance the novelty of the proposed approach, we have relaxed Assumptions 2, 5 and 6 of the previous manuscript in the revised manuscript.

Major Comment 3: *The problem formulation should not be inside the introduction section. Usually, problem formulation contains detailed mathematical derivation.* .

Author's Response: Thank you again for raising this concern, as mentioned in the previous comment (Major Comment 2), we have moved the problem formulation, which was previously inside introduction section to the Section III-A (Problem Description) that discusses the major issues supported by their mathematical representations in the revised manuscript.

Major Comment 4: *In the introduction part, the contribution is not clear.* .

Author's Response: To address this concern, we have titled the main contributions in Section I-C followed by brief discussions. Furthermore, we have rephrased several sentences and avoided the use of confusing statements/words in the introduction section (including Section III-C) to enhance the brevity and clarity of the paper, for instance, "To capture the variations induced in the system, we characterize the distribution functions..." in contribution 2 of the Section I-C is replaced with "To capture the variations induced due to imperfect channel knowledge, we characterize the distribution functions..." in the revised manuscript.

Minor Comment 1: *Line 31 of Page 1, "Interweave Systems (ISs)" should be "interweave systems (ISs)". The same error also happens in Cognitive Radio (CR), Secondary User (SU) ...*

Author's Response: We have address this comment in the revised manuscript.

Minor Comment 2: *Line 35 of Page 2, "In contrast, the spectrum below 6 GHz..." should be "In contrast, the spectrum beyond 6 GHz..."*

Author's Response: We have rephrased this statement in the introduction of the revised manuscript, where we mention, "Besides the spectrum beyond 6 GHz, an efficient utilization of the spectrum below 6 GHz presents an alternative solution.".

Minor Comment 3: *What is the meaning of cf. ? For example, the "cf." in Line 45 of Page 6, "we extend this concept to the IS, hence, employ.channels, cf. Fig.1.".*

Author's Response: We have replaced the abbreviation cf.[3] with their comparable counterparts such as see, compare, refer, consider, etc.

Dear Reviewer 3,

Thank you very much for appreciating our work, and providing your ~~valuable suggestions and~~ insightful comments on our manuscript. The detailed revisions are listed in the following points.

Comment 1: *The paper is kind of verbose, especially the Introduction section which spans over 6 pages*

[3]cf. corresponds to conferre in Latin. In English it can be replaced with compare, refer, etc.

(from page 2 to page 8).

Author's Response: Thank you for raising this concern. In order to address this issue, we have moved the problem formulation, which was previously inside introduction section to the Section III-A (Problem Description) that highlights the major issues supported by their mathematical formulation in the revised manuscript. Besides that, we have revised the introduction section by rephrasing several sentences such as "In contrast, the spectrum below 6 GHz, which is appropriate especially for mobile communications, presents an alternative solution." in the second paragraph of introduction section is replaced with "Besides the spectrum beyond 6 GHz, an efficient utilization of the spectrum below 6 GHz presents an alternative solution." in the revised manuscript, this is done to enhances the brevity and lay emphasis on the main contributions of the paper. In this way, we were able to squeeze the introduction section to four and a half pages.

Comment 2: *The novelty of Section III is unclear. It appears that the only new element is the introduction of a short estimation time divided from the frame time T. The presented models are simply derived from existing references.*

Author's Response: ~~We agree with the reviewer's comment that Section III mainly involves the careful integration of estimation process in the frame structure~~. In this perspective, we have emphasized the novelty of this Section III by considering different aspects in the revised manuscript, for instance, in the previous manuscript, we considered the estimation and the sensing as two disjoint events, refer Assumption 2 in the previous manuscript. However, in the revised manuscript, we combine the samples obtained from the estimation and the sensing phases, in this way, we further enhance the performance of our proposed approach in terms of the sensing-throughput tradeoff. Furthermore, in Section III-C of the revised manuscript, we have addressed a major concern regarding the validity of the estimated parameters. To this end, we have proposed a novel methodology that considers a joint estimation and (coarse) detection at the end of the estimation phase. Taking into account these aspects in the revised manscript, we have relaxed Assumptions 2, 5 and 6 of the previous manuscript in our proposed approach.

Concerning the second part of the reviewer's comment, which states, ~~*The presented models are simply derived from existing references.*~~ we have further emphasized in contribution 1 of the introduction section and the Section III-B of the revised manuscript that the estimation methods are proposed such that they deliver a decent tradeoff between reliability complexity and versatility (to a larger range of

primary systems) of the proposed framework, as a result, facilitates the hardware realizability of the proposed framework. In this regard, we have proposed a received power estimation for the sensing and the interference channels.

Comment 3: *In the objective functions (average throughput) in Theorem 1 and 2, C and P_d should be independent in order to get those expressions in (30) and (32). The authors should explain this point.*

Author's Response: We have addressed this concern in revised manuscript, refer Appendix-A, where we mention, "Given that the random variables $\mathrm{P_d}(\hat{P}_{\mathrm{Rx,ST}})$, $\mathrm{C_0}(|\hat{h}_{\mathrm{s}}|^2)$ and $\mathrm{C_1}(|\hat{h}_{\mathrm{s}}|^2, \hat{P}_{\mathrm{Rx,SR}})$ are functions of $\hat{P}_{\mathrm{Rx,ST}}$, and $|\hat{h}_{\mathrm{s}}|^2$ and $\hat{P}_{\mathrm{Rx,SR}}$, which are independent random variables. Applying the independence property to obtain

$$\mathbb{E}_{\mathrm{P_d,C_0,C_1}}\left[\mathrm{C_0}(1-\mathrm{P_{fa}})+\mathrm{C_1}(1-\mathrm{P_d})\right]=\mathbb{E}_{\mathrm{C_0}}\left[\mathrm{C_0}\right](1-\mathrm{P_{fa}})+\mathbb{E}_{\mathrm{C_1}}\left[\mathrm{C_1}\right]\mathbb{E}_{\mathrm{P_d}}\left[(1-\mathrm{P_d})\right]$$

in (28) and (30)."

Comment 4: *Theorem 1 and 2 only consider that the estimation time is fixed and given. Since both τ_{sen} and τ_{est} are parameters involved in the distributions, the maximization in (30) and (32) may take both of them into account.*

Author's Response: Thank you for pointing this out. We have addressed this concern in the revised manuscript, refer (28) and (30). In addition to that, to procure further insights into the objective functions that depict the estimation-sensing-throughput tradeoff stated in (28) and (30), we have included Figure 8 in the revised manuscript that considers the variations of the average secondary throughput along the estimation time and sensing time.

Many thanks again for your assistance in this review process, which leads to significant improvement of this work. If further revision is required, we would be very happy to address future comments in this manuscript.

Sincerely yours,

Ankit Kaushik

Shree Krishna Sharma

Symeon Chatzinotas

Björn Ottersten