Response to Editor's Comments

Your Comment: The reviewers pointed out several important issues of the paper. In particular, the novelty of the proposed work should be better justified (as mentioned by Reviewer 1 and 2). Please discuss the uniqueness of the work in this paper in the context of related work and challenges, and properly explain the contributions based on the uniqueness. In addition, major assumptions used in the proposed work should be properly justified (as pointed out by Reviewer 1, 2, and 3). The performance evaluation part should also be strengthened.

Our Response: Thank you very much for your effort on handling our manuscript. We appreciate it very much. We have carefully studied the reviewers' comments and revised the manuscript accordingly. We provide a point-to-point response to the reviewers' comments below and hope that the reviewers would be satisfied with our revisions. In what follows, we highlight the novelty and contributions of our work in response to the main concern of Reviewer 1 and 2.

The ***novelty*** of our work lies in the design of a blind interference cancellation (BIC) technique. With this BIC technique, a multi-antenna wireless receiver is capable of decoding its data packets in the presence of unknown interference. More importantly, this BIC technique is amenable to practical implementation. Our experimental results show that it can achieve an average of 33 dB cancellation capability for unknown interference in real-world wireless environments. For the first time, our design and experimentation demonstrated that heterogeneous wireless networks can use the same spectrum band at the same time, even if they have no mutual knowledge, no cross-network coordination, and no fine-grained synchronization. More specifically, the ***contributions*** of our work can be summarized as follows:

- **An Interference-Resistant Wireless Receiver:** We have designed a new BIC technique for a wireless receiver by leveraging recent advances in MIMO technology. The new wireless receiver is capable of decoding its data packets in the presence of unknown interference (unknown interference waveform and unknown interference power). We have implemented such a wireless receiver on a wireless testbed and demonstrated that it can work in real time in real-world wireless environments. (see related demo video's link below). Our experimental results show that the proposed BIC technique achieves an average of 33 dB cancellation for unknown interference in an indoor environment. This means that, even if the interference is 20 dB stronger than the signal of interest, the receiver can still decode its data packets by using QPSK modulation and LDPC channel coding.
- **A Blind Beamforming (BBF) Technique:** We have proposed a new BBF technique for a multi-antenna wireless transmitter, which can pre-cancel its generated interference for an unintended receiver. Particularly, this BBF technique does not need to have channel knowledge for beamforming; instead, it uses overheard unknown interference for beamforming filter design. This BBF technique is completely different from zero-forcing beamforming technique. We will further explain it in details in the following. We have implemented this BBF on a wireless testbed and demonstrated that it achieves 25 dB pre-cancellation capability for the unintended receiver in real-world wireless environments.
- **A Real-Time Spectrum Sharing System:** To the best of our knowledge, this work is the first one that demonstrates real-time concurrent spectrum utilization of two real-world wireless networks in the absence of cross-network collaboration. This work made a concrete step from the theoretical exploration of spectrum sharing toward its practical application in real-world wireless systems.

Demo video: `http://www.ece.louisville.edu/hzeng/spectrum_sharing.html`

Response to Reviewer 1's Comments

Your Comment: This paper considered an underlay spectrum sharing for CRNs. The main points of this paper are to propose IC techniques at the secondary transmitter (used to design partial beamforming) and at the secondary receivers (used to detection and canceling the primary interference). After reviewing the paper very carefully, I believe that the contributions of the paper are not significant and the proposed method is lack of novelty. Please see my comments detailed in the following.

Our Response: Thank you very much for reviewing our manuscript. I would like to take this opportunity to address your concerns about this work's contributions and novelty. Before doing so, we would like to point out that this paper is a system-level work aiming to solve the important problem of spectrum sharing in realistic scenarios. Indeed, this is not a theoretical work aiming to explore the network capacity limits.

Contributions: This work advances the state-of-the-art in the following aspects:

- **An Interference-Resistant Wireless Receiver:** We have designed a new BIC technique for a wireless receiver by leveraging recent advances in MIMO technology. The new wireless receiver is capable of decoding its data packets in the presence of unknown interference (unknown interference waveform and unknown interference power). We have implemented such a wireless receiver on a wireless testbed and demonstrated that it can work ***in real time*** in real-world wireless environments. (see related demo video in [Ref-1]). Our experimental results show that the proposed BIC technique achieves an average of 33 dB cancellation for unknown interference in an indoor environment. This means that, even if the interference is 20 dB stronger than the signal of interest, the receiver can still decode its data packets by using QPSK modulation and LDPC channel coding.

  In addition to its application in CRNs, this new wireless receiver has many other important applications in wireless networks, such as securing wireless communications against radio jamming attacks, enhancing Wi-Fi reliability in the face of unknown co-channel interference, and improving cell-edge users' performance in the presence of inter-cell interference.

  It is noteworthy that, although there are many interference management techniques in the literature (e.g., interference cancellation, interference mitigation, interference alignment, interference neutralization, etc.), most of them are limited to cooperative wireless networks and require the knowledge about interference. ***The novelty of our design*** is that it does not require the receiver to have the knowledge of interference for signal detection. It does not require channel estimation either. This is a significant difference between our design and the prior works.

- **A Blind Beamforming (BBF) Technique:** We have proposed a new BBF technique for a multi-antenna wireless transmitter, which can pre-cancel its generated interference for an unintended receiver. Particularly, this BBF technique does not need to have channel knowledge for beamforming; instead, it uses overheard unknown interference for beamforming filter design. This BBF technique is completely different from zero-forcing beamforming technique. We have implemented this BBF on a wireless testbed and demonstrated that it achieves 25 dB pre-cancellation capability for the unintended receiver in real-world wireless environments.

- **A Real-Time Spectrum Sharing System:** To the best of our knowledge, this work is the first one that demonstrates real-time concurrent spectrum utilization of two real-world wireless networks in the absence of cross-network collaboration (demo video available in [Ref-1]). This work made a concrete step from the theoretical exploration of spectrum sharing toward its practical application in real-world wireless systems.

We hope that the reviewer would review this work from the system-level perspective and position it inside the landscape of practical design and implementation of spectrum sharing solutions.

[Ref-1] Demo video: `http://www.ece.louisville.edu/hzeng/spectrum_sharing.html`

Your Comment: The proposed blind beamforming is not new and quite impractical. In particular, the secondary transmitter constructs a spatial filter based on the interfering signal sent by the primary user, and this spatial filter must ensure that there is no interference to the primary receiver. Such a design is quite similar to the Zero-Forcing precoding, as shown in (6), (7), and Remark 2.

Our Response: *First*, we do not understand why the reviewer argued "the proposed blind beamforming technique is quite impractical," since we have already implemented it on a wireless testbed and demonstrated its real-time performance in a real-world indoor wireless environment. *Second*, the spatial filter is not to ensure that there is no interference to the primary receiver. Rather, it reduces the interference power for the primary receiver and, hopefully, the interference power will be reduced below the primary receiver's noise floor. *Third*, the proposed blind beamforming technique is fundamentally different from the existing zero-forcing precoding and its variants. In what follows, we elaborate on why zero-forcing precoding is not a good option for beamforming in underlay CRNs.

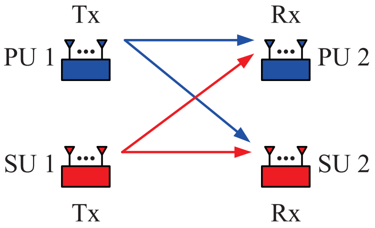


Figure 1: Concurrent spectrum utilization of primary users (PUs) and secondary users (SUs).

Consider the network shown in Fig. 1 as an example. If SU 1 wants to use zero-forcing precoding to handle the interference from itself to PU 2, it then needs to obtain the channel from itself to PU 2, i.e., $\mathbf{H}_{21}$. With the knowledge of this channel, SU 1 can construct its zero-forcing precoder by $\mathbf{P} = \mathbf{H}_{21}^{\mathsf{H}}(\mathbf{H}_{21}\mathbf{H}_{21}^{\mathsf{H}})^{\dagger}$, where $(\cdot)^{\dagger}$ denotes pseudo-inverse operation and $(\cdot)^{\mathsf{H}}$ is conjugate transpose operation. Therefore, for zero-forcing precoding, it is of great importance for SU 1 to acquire channel knowledge $\mathbf{H}_{21}$. Generally speaking, there are two methods for SU 1 to obtain channel knowledge $\mathbf{H}_{21}$: *Explicit* feedback and *implicit* feedback. We describe these two feedback methods and point out their limitations as follows:

- In the *explicit feedback* method, SU 1 requires PU 2 to estimate the channel and send the channel information to itself. However, this method does not work in underlay spectrum sharing paradigm because primary users are not cooperative.
- In the *implicit feedback* method, SU 1 overhears the interfering signal from PU 2 when it is transmitting and estimates the channel. Then, SU 1 uses the estimated channel to construct the precoder for interference pre-cancellation (assuming that channel has been calibrated to maintain reciprocity). Nevertheless, this method suffers from two fundamental problems and does not serve our purpose. i) SU 1 needs to know the primary user's signal waveform, frame format, and reference signal values. This information may not be available to the secondary users in real systems. ii) More importantly, SU 1 needs additional RF chain and baseband processing modules to estimate the channel even if it has the above knowledge. For example, suppose that primary users are LTE devices and secondary users uses Wi-Fi protocols for communications. Then, if SU 1 wants to estimate channel knowledge $\mathbf{H}_{21}$, it needs to have LTE's RF chain and baseband processing modules to estimate the channel. This is because LTE and Wi-Fi have different RF chain parameters (e.g., LTE sampling rate is 30.72 MHz while Wi-Fi sampling rate is 20 MHz) and different baseband parameters (e.g., LTE FFT point is 512, 1024,

or 2048 while Wi-Fi FFT point is 64). The requirement of an additional RF/baseband component not only increases the hardware cost but it also accelerates the power consumption.

Since zero-forcing precoding requires cross-network channel knowledge, it is not a good choice for beamforming in underlay CRNs. In contrast, the proposed blind beamforming technique constructs the beamforming filter using the overheard interfering signals from the primary users. It does not need to have an additional set of RF chain and baseband modules for the beamforming filter construction. For the above example, Wi-Fi-based SU 2 can use its Wi-Fi RF chain and baseband modules to receive the interfering signal from the LTE-based primary device for beamforming filter construction, making the proposed technique amenable to real-system implementation.

Your Comment: In (6), it may not be correct since the average interference at the secondary user should be divided by L_p. Also, it is not clear what value of L_p was used in the paper.

Our Response: We guess that the reviewer refers to (7) rather than (6). Equation (7) is correct since $\sum_{l=1}^{L_\mathrm{p}} \mathbf{Y}(l,k)\mathbf{Y}(l,k)^*$ and $\frac{1}{L_p}\sum_{l=1}^{L_\mathrm{p}} \mathbf{Y}(l,k)\mathbf{Y}(l,k)^*$ have the same eigenvectors. In our design, we use eigenvectors corresponding to the minimum eigenvalues to construct the beamforming filter. L_p is the number of overheard interfering signal samples at the secondary device (e.g., $L_\mathrm{p} = 20$). We have clarified this parameter on page 5 of the revised manuscript.

Your Comment: In Fig. 4, the proposed spectrum sharing scheme is quite artificial. For example: what will happen if PU2 still transmits the signals to PU1 during Phase II? This is because of the fact that the secondary system does not know the transmission schedule of the primary system. As such, the proposed solution in this work can not be adapted to real scenarios.

Our Response: The main contribution of this work is the design of a practical blind interference cancellation technique, which enables a multi-antenna receiver to decode its data packet in the presence of unknown interference. Coming back to the reviewer's question regarding the proposed spectrum sharing MAC protocol, we have the following arguments.

1. Our design is based on the assumption that the two-way traffic in the primary network is consistent and persistent (see section of Problem Statement on page 3 and page 4 of the revised manuscript). This type of traffic is common in real wireless systems. For example, in a TDD-based cellular network, the downlink and uplink time slots in a frame are fixed, and thus the forward and backward traffic is consistent; in a Wi-Fi network with a single active user watching online video, the two-way traffic is also consistent and persistent. With such a primary network, it is easy for the secondary network to ***learn*** the direction and duration of the primary traffic, even though the secondary network has no knowledge about the primary network. Based on its ***learned*** information, the secondary network can align its transmission with the primary network's traffic, as we presented in the paper.

2. "What will happen if PU2 still transmits the signals to PU1 during Phase II?" We can prevent this case by detecting the source of interfering signal at the secondary devices. That is, the secondary devices send signals only if they detect the interference signal from PU 1; they remain silent whenever they detect the interference signal from PU 2. Since the secondary devices have multiple antennas, it is easy for them to identify the source of interfering signal by leveraging the channels' spatial signature.

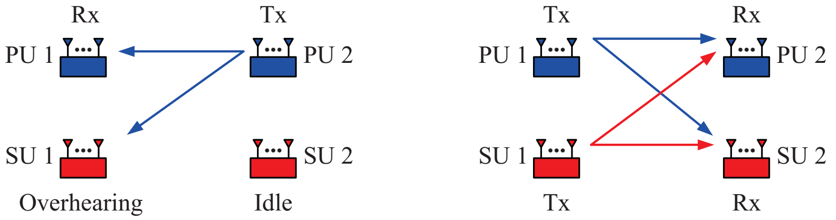
In page 3 and page 4 of the revised manuscript, we have added the following paragraph to clarify the mechanism in the revised manuscript. We copy it below for your review.

"When the primary network has consistent and persistent bidirectional traffic, it is easy for secondary devices to learn primary transmission direction and duration by leveraging wireless signals' spatial signature (e.g., signal angle-of-arrival). Based on the learned information, the secondary network can align its transmissions with the transmissions in the primary network, as illustrated in Fig. 3. It is noteworthy that the time alignment of primary and secondary transmissions is loose, owning to BBF and BIC at the PHY layer. To ensure that the secondary transmissions will not disrupt the primary transmissions, SU 1 transmits its signals only after it detects the interfering signals from PU 2."

Your Comment: The assumption "In the time domain, Phase I aligns with the backward packet transmission in the primary network, and Phase II aligns with the forward packet transmission in the primary network, as illustrated in Fig. 3" is also not practical. Please note that packet transmissions (Forward & Backward packets) are not known at the secondary users.

Our Response: As we explained in the response to your previous comment, a secondary device can ***learn*** the primary traffic direction and duration by leveraging its multiple antennas. Specifically, a secondary device in Fig. 2 can overhear the interfering signal from a primary device and estimate its source (PU 1 or PU 2) by exploiting the interfering signal's spatial signature (e.g., distribution of singular values or angle-of-arrival). The secondary devices then determine their own transmission activities based on their learned information about the primary network. To avoid disrupting the primary traffic, SU 1 transmits signals only if it detects the interfering signal from PU 2.

It is worth pointing out that ***doing so does not require fine-grained synchronization between the primary and secondary networks***. As illustrated in Fig. 3, the secondary transmission is not necessarily aligned with the primary transmission perfectly due to the half-duplex guard interval in most real-world wireless systems. The secondary devices can use a small amount of time, from t_3 to t_4 in Fig. 3, to infer the source of the overheard interfering signal. Once it is found that the interfering signal is from PU 2, SU 1 transmits its signal and SU 2 receives the desired signal.



(a) Phase I: SU 1 overhears the interfering signals from PU 2

(b) Phase II: SU 1 sends data to SU 2 using IC techniques

Figure 2: Illustration of our proposed spectrum sharing scheme.

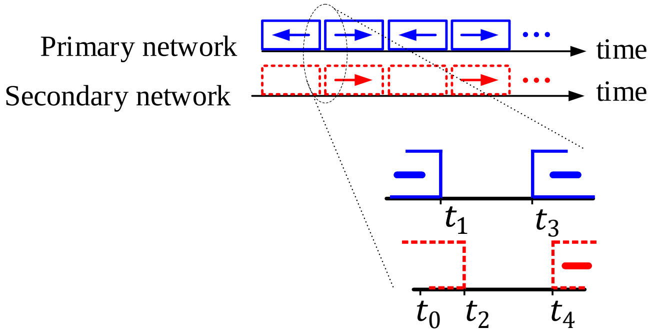


Figure 3: Micro-scale illustration of inter-network synchronization.

Your Comment: In addition, waiting a time slot to hearing the interfering signals from the primary users is waste resource of the secondary systems. From this, comparison with other designs is required.

Our Response: Unfortunately, there is no spectrum sharing scheme in the literature that we can use as the benchmark for performance comparison. This is because there is no technique in the literature that can be used for a secondary receiver to decode its desired packets in the presence of unknown interference. For this reason, the existing spectrum sharing schemes in the literature are limited to either theoretical exploration or practical design in cooperative networks. To the best of our knowledge, our work, along with our demo system (`http://www.ece.louisville.edu/hzeng/spectrum_sharing.html`), represents the first solution to enabling real-time concurrent spectrum utilization for heterogeneous wireless networks in the absence of cross-network coordination, fine-grained synchronization, and mutual knowledge (e.g., waveform and frame format).

Response to Reviewer 2's Comments

Your Comment: In this paper, the authors proposed a MIMO-based spectrum sharing scheme for a small cognitive radio network with a single pair of PUs and SUs. The major contribution of this work is the implementation of the proposed scheme on a wireless testbed with extensive experiments. Overall, the presentation and organization of this work are good. However, the reviewer is concerned about the over-simplicity of the system model. Please see detailed comments in the following.

Our Response: Thank you very much for your review and constructive comments, which helped us improve the quality of this work. In this revision, we have carefully revised our manuscript based on your comments, questions, and suggestions. The rewritten parts are highlighted in blue color. The detailed point-by-point responses are provided below.

Your Comment: In the system model, only a single PU pair and a SU pair are considered. The reviewer is not fully convinced by the justification provided by the reviewer. First, there are a lot of existing work studying the multiple PU and SU pairs in CRNs, the single-pair user model may be oversimplified. Although from the implementation point of view, the novelty of this work may be sufficient, the simplified model significantly limits the theoretical contribution.

Our Response: There is indeed a large volume of work in the literature studying CRNs that consist of multiple pairs of primary and secondary users. In fact, the research on spectrum sharing in wireless networks has been active for almost two decades. However, the existing work is limited to theoretical exploration, signal processing, network protocol, and architecture design for spectrum sharing in cooperative wireless networks. Thus far, little progress has been made in the design of spectrum sharing wireless systems in the absence of cross-network coordination and inter-network knowledge. Our work fills this gap.

Despite considering a single PU pair and a single SU pair, ***our work is the first one that enables real-time spectrum sharing for two heterogeneous wireless networks in the absence of cross-network coordination, fine-grained synchronization, and mutual knowledge (e.g., waveform and frame structure)***. Moreover, we have built a prototype of our spectrum sharing solution on a wireless testbed, and demonstrated its practicality and effectiveness in real-world wireless environments. A video of our demo can be found here: `http://www.ece.louisville.edu/hzeng/spectrum_sharing.html`

As you mentioned, the contribution of our work is not in theory but in practical solution design. Specifically, we have designed a blind interference cancellation technique, which enables a multi-antenna receiver to decode its data packets in the presence of unknown interference. We have also designed a blind beamforming technique, which pre-cancels its generated interference for an unintended receiver in the absence of channel knowledge. Moreover, we have validated the performance of these two techniques in real-world wireless scenarios.

Although simple, the network (one PU pair and one SU pair) considered in our work is a fundamental building block for a large-scale CRN. Our spectrum sharing scheme can be extended to a large-scale CRN that comprises many pairs of primary and secondary users. We elaborate on this point in our response to your next concern.

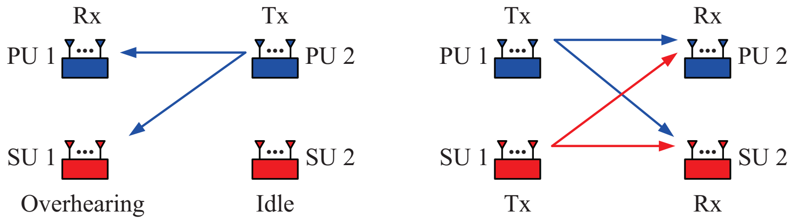
Your Comment: Second, if possible, the reviewer expect the authors could further explain the challenge of considering multiple user pairs, and discuss this potential extension.

Our Response: Although our design was presented for a small-size network comprising one PU pair and one SU pair, it can be extended to a large-scale network that consists of many PU pairs and many SU pairs.

This is because in most real-world wireless networks (e.g., Wi-Fi and cellular), only one user pair is active on a frequency band at a time. For example, in a Wi-Fi network, only one Wi-Fi client device is active for communicating with Wi-Fi router owing to the CSMA MAC protocol. Therefore, our design is a building block for spectrum sharing in a large-scale network where a secondary device has more antennas than a primary device. To clarify this point, we have discussed the potential extension and possible challenges on page 12 of the revised manuscript. We copy them below for your review.

"In this work, we presented a spectrum sharing scheme for a small-size CRN consisting of one PU pair and one SU pair. This spectrum sharing scheme can be extended to a large-scale CRN that comprises multiple PU pairs and multiple SU pairs. This is because in most real-world wireless networks (e.g., Wi-Fi and cellular), only one user pair is active on a frequency band at a time. Therefore, our current design is a fundamental building block for spectrum sharing in a large-scale CRN. Nevertheless, extending our design to a large-scale CRN still faces several challenges. First, a secondary device should be capable of learning the active PU devices over time as well as their transmission direction and duration. For a secondary device, how to accurately obtain this information through a learning procedure is a challenging task. Second, primary devices may not be stationary (e.g., vehicular and unmanned aerial networks). How to design a more adaptive and intelligent spectrum sharing MAC protocol for the secondary network is another challenging task. These challenges will be addressed in our future work."

Your Comment: The authors are suggested to explain the technical challenge of this work. Particularly, why the authors have to redesign a new scheme but not implement the existing ones in the literature?



(a) Phase I: SU 1 overhears the interfering signals from PU 2.

(b) Phase II: SU 1 sends data to SU 2 using IC techniques.

Figure 4: Illustration of our proposed spectrum sharing scheme.

Our Response: The technical challenges lie in the interference cancellation in Fig. 4(b). To enable transparent spectrum sharing, the secondary users must take the full responsibility for interference cancellation. More specifically, SU 1 needs to pre-cancel its generated interference for PU 1, and SU 2 needs decode its desired signal in the presence of cross-network interference from PU 1. In what follows, we state the challenges in our design and explain why the existing schemes in literature do not work.

- **Challenges in Blind Interference Cancellation (BIC):** First of all, we want to point out that ***there is no technique in the literature that can decode the signal in the presence of unknown interference***. Our BIC technique is the first one of this kind.

  One may argue that multi-user MIMO (MU-MIMO) detector could decode the packets in the face of inter-user interference. This is true. However, MU-MIMO detector cannot be used here. This is because MU-MIMO works only for homogeneous networks where all the users have the same waveform, frame format, and fine-grained synchronization. In our network, primary and secondary networks use different waveforms and different frame formats, and there is no fine-grained synchronization between primary and secondary users. Therefore, MU-MIMO detector does not work in our network scenario.

One may also argue that successive interference cancellation (SIC) can decode data packets in the face of interference. This is right; however, SIC can decode data packets only in the face of *strong* interference. If the interference has the same power level as the desired signal, SIC would fail. In our network scenario, there is no guarantee that the interference at SU 2 is much stronger than its desired signal. Therefore, SIC is not a generic solution for SU 2, let alone SIC requiring to have the full knowledge of primary communications (e.g., waveform, frame format, reference signals, etc.).

One may further argue CDMA and frequency hopping are possible solutions for interference cancellation at SU 2. In fact, these two techniques are notorious for their low efficiency in spectrum utilization. For this reason, these two techniques are almost out of history and never considered for next-generation wireless systems.

In a nutshell, our BIC technique is the first one that can decode data packets in the face of unknown interference. The novelty of our design is that we use the interfered packets preamble to train a spatial filter for interference cancellation and signal detection. This is fundamentally different from existing interference cancellation techniques, which always try to estimate the wireless channel and then use the estimated channel for signal detection. Meanwhile, our BIC technique is amenable to real-world implementation. In addition to the spectrum sharing, it has many other applications such as co-channel interference management in Wi-Fi, inter-cell interference management in 5G, and resilience against jamming attacks.

- **Challenges in Blind Beamforming (BBF):** Although there are many beamforming techniques in the literature, most of them require channel knowledge for the construction of beamforming precoders. ***Our work is the first one showing via experimentation that channel knowledge is not necessary for beamforming.*** Our BBF technique exploits the statistical characteristics of unknown interference to construct the beamforming filters, which appear to be very effective for interference pre-cancellation in our experiments.

  One may wonder what is the difference between BBF and the existing beamforming methods. To explain the difference, let us consider the network in Fig. 4. Suppose that the primary network is LTE and the secondary network is Wi-Fi. With the existing beamforming techniques, SU 1 first overhears the interfering signal from PU 2, as shown in Fig. 4(a), and uses the overheard interfering signal to estimate the channel between itself and PU 2. Then, SU 1 uses the estimated channel to construct beamforming filters for interference pre-cancellation, as shown in Fig. 4(b). In this method, there are two requirements: i) SU 1 knows the waveform, frame format, and reference signals of the primary signals; ii) SU 1 needs to be equipped with both LTE and Wi-Fi RF chains. Specifically, SU 1 needs to have LTE RF chain to estimate the channel between itself and PU 2, and SU 1 needs to have Wi-Fi RF chain for its own communications. These two requirements significantly limit the application of existing beamforming techniques in cognitive radio networks.

  In contrast, our proposed BBF technique does not have these two requirements. Specifically, it requires neither the knowledge of primary signals nor additional RF chains for channel estimation. It uses statistical characteristics of the interfering signals to construct the beamforming filters within its own RF chain. Moreover, our experimental results show that it is every effective in real-world wireless environments.

We have revised the manuscript to emphasize the challenges of our work. We highlighted the challenges on page 4 of the revised manuscript. We copy it below for your review.
“**Challenge 1:** Referring to Fig. 4(b), the main task of the secondary transmitter (SU 1) is to pre-cancel its generated interference at the primary receiver (PU 2). Note that we assume the secondary transmitter has no knowledge about the primary network, including the signal waveform, bandwidth, and frame structure. The primary network may use OFDM, CDMA, or other types of modulation for packet transmissions. The lack

of knowledge about the interfering signals from the primary transmitter makes it challenging to manage the interference on the secondary network.

Challenge 2: Again, referring to Fig. 4(b), the main task of the secondary receiver (SU 2) is to decode its desired signals in the presence of cross-network interference from the primary transmitter. Note that the secondary receiver has no knowledge of the interference characteristics, and that the primary and secondary networks may use different waveforms and frame formats for their transmissions. The lack of inter-network coordination, fine-grained synchronization, and mutual knowledge makes it challenging to tame interference for signal detection."

Response to Reviewer 3's Comments

Your Comment: In this manuscript, the authors proposed a practical spectrum sharing scheme for a small CRN that comprises a pair of primary users and a pair of secondary users. Specifically, the BBF and BIC schemes were designed to enable the developed protocol without the knowledge of PUs. A prototype of the developed scheme was constructed and experimental results were also provided. The main comments and concerns of the reviewer are listed as follows.

Our Response: Thank you very much for your review and constructive comments, which helped us improve the quality of this work. In this revision, we have carefully revised our manuscript based on your comments, questions, and suggestions. The rewritten parts are highlighted in blue color. The detailed point-by-point responses are provided below.

Your Comment: The authors assume that the number of antennas for the SU is greater than that for the PU. If PU has more antennas, can the developed scheme work? If no, it seems the contribution of this paper decreases.

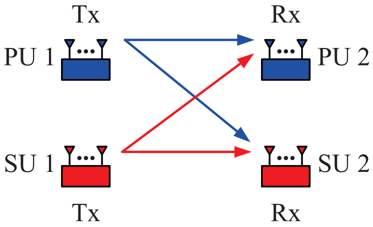


Figure 5: A CRN consisting of two active primary users and two active secondary users.

Our Response: Our spectrum sharing scheme works as long as the number of antennas on a secondary device is greater than the number of data streams in the primary transmission. Mathematically, denote p as the number of data streams in the primary transmission. Denote q as the number of data streams in the secondary transmission. Denote M_{stx} as the number of antennas on the secondary transmitter (SU 1). Denote M_{srx} as the number of antennas on the secondary receiver (SU 2). Then, M_{stx} and M_{srx} should meet the following constraints: $M_{\text{stx}} \geq p + q$ and $M_{\text{srx}} \geq p + q$.

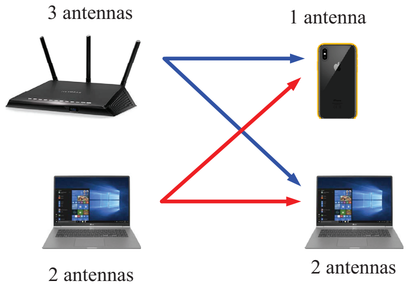


Figure 6: An example of spectrum sharing in a CRN where a primary device has more antennas than a secondary device.

Fig. 6 is an example of spectrum sharing in a cognitive radio network where a primary device has more antennas than a secondary device. In this network, since the phone in the primary network has one antenna, the primary network can only support one data stream even though the Wi-Fi router has three antennas. For the secondary network where the laptops have two antennas, it can support one data stream and cancel the interference between itself and the primary network. Using our spectrum sharing scheme, both primary and secondary networks can support one data stream, without the need of cross-network coordination and inter-network knowledge.

It is worth pointing out that these two constraints ($M_{\text{stx}} \geq p+q$ and $M_{\text{srx}} \geq p+q$) are from the degree-of-freedom (DoF) limitation in the spatial domain. Therefore, these two constraints are not just for our specific design, but apply to any spectrum sharing scheme.

Your Comment: The developed protocol is based on the assumption that SUs are synchronized with PUs. However, as mentioned by the authors, SUs know nothing about PU. In this way, how can the synchronization between SU and PU establish?

Our Response: In wireless networks, the synchronization requirement varies depending on its purposes. Generally speaking, the synchronization requirement can be classified into two categories: PHY-layer synchronization and MAC-layer synchronization.

- PHY-layer synchronization requires multiple signal frames to be aligned within one signal sample. For example, a Wi-Fi network has 20 MHz bandwidth; therefore, the PHY-layer synchronization in Wi-Fi requires the time misalignment of multiple signal frames to be less than 50 ns. This type of synchronization is needed for PHY-layer transmission techniques such as uplink MU-MIMO.
- MAC-layer synchronization has a loose requirement on time alignment, which could be as large as 10 µs. Such a synchronization requirement can be easily achieved at the MAC layer.

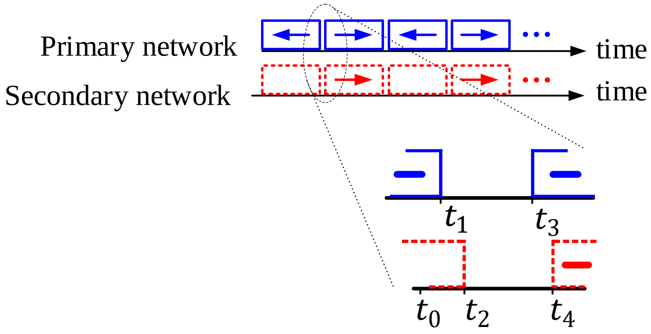


Figure 7: Illustration of inter-network MAC-layer synchronization.

Our proposed spectrum sharing scheme does not require PHY-layer synchronization; it only requires MAC-layer synchronization. As shown in Fig. 7, the proposed spectrum sharing scheme does not require perfect time alignment between the primary and secondary transmissions, thanks to the blind beamforming and blind interference cancellation techniques at the PHY layer. Therefore, the secondary devices can achieve the MAC-layer synchronization through a learning procedure. Recall that we assumed in the manuscript that the bidirectional traffic in the primary network is persistent and consistent. The secondary devices can easily learn the duration of the primary transmission in each direction. In addition, since a secondary device is equipped with multiple antennas, it is easy to infer the direction of a primary transmission by exploiting the interfering signal's spatial signature (e.g., distribution of singular values or signal angle-of-arrival). The secondary network is capable of achieving the synchronization required by our spectrum sharing scheme.

We have revised the manuscript to clarify the synchronization requirement. The revised part is on page 3 and page 4 of the revised manuscript. We copy it below for your review.

"When the primary network has consistent and persistent bidirectional traffic, it is easy for secondary devices to learn primary transmission direction and duration by leveraging wireless signals' spatial signature (e.g., signal angle-of-arrival). Based on the learned information, the secondary network can align its transmissions with the transmissions in the primary network, as illustrated in Fig. 3. It is noteworthy that the time alignment of primary and secondary transmissions is loose, owning to BBF and BIC at the PHY layer. To ensure that the secondary transmissions will not disrupt the primary transmissions, SU 1 transmits its signals only after it detects the interfering signals from PU 2."

Your Comment: The developed BBF scheme employs a quite strong assumption, i.e., the noise power is zero and the forward/backward channels are reciprocal. However, in realistic network, the noise power is not zero and the channel reciprocity may not hold in many scenarios. In this way, how can the performance of BBF be guaranteed?

Our Response: These two assumptions (zero-noise and channel reciprocity) were made only for theoretical analysis. Theoretically, when the noise is zero and the channel is reciprocal, the proposed BBF technique can ***completely*** pre-cancel interference for the primary receiver. Again, these two assumptions are only for theoretical analysis of our proposed BBF technique. As shown in our experimental results and our real-time demo (`http://www.ece.louisville.edu/hzeng/spectrum_sharing.html`), the BBF technique does work in real-world wireless environments. In what follows, we elaborate on these two assumptions in real-world wireless systems.

- **Channel Reciprocity:** In real-world wireless systems, the assumption of channel reciprocity can be fulfilled through channel calibration, which has been widely used in real-world wireless systems. In our experiments, we implemented the channel calibration algorithm in [Ref-2] to preserve relative channel reciprocity. Specifically, referring to Fig. 8, we applied a matrix $\mathbf{C}$ to the baseband signal processing on SU 1. With $\mathbf{C}$ at SU 1, the forward and backward channels satisfy the following constraint: $\mathbf{D}\mathbf{H}_{sp} = \mathbf{C}\mathbf{H}_{ps}$, where $\mathbf{D}$ could be any diagonal matrix, $\mathbf{H}_{sp}$ is the channel from PU 2 to SU 1, and $\mathbf{H}_{ps}$ is the channel from SU 1 to PU 2. As long as this constraint is satisfied, the channel reciprocity is maintained and our BBF technique works.

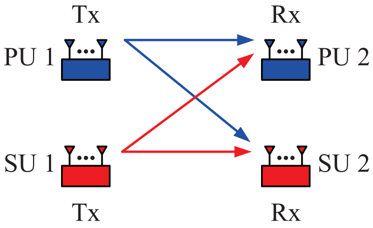


Figure 8: Co-existing primary and secondary networks.

- **Noise Power:** The assumption of zero-noise is only for the exploration of the performance limits of our BBF technique. Our BBF technique also works in noisy scenarios. This is demonstrated by our experimental results and our real-time demo. Our extensive experimental results show that, in the presence of noise and channel calibration, our BBF technique achieves an average of 25 dB pre-cancellation capability for the interference at 12 different locations (i.e., SU 1's capability of pre-cancelling its generated interference for PU 2 in Fig. 8). This indicates that our BBF technique works in real-world wireless environments.

[Ref-2] C. Shepard, H. Yu, N. Anand, E. Li, T. Marzetta, R. Yang, and L. Zhong, “Argos: Practical many-antenna base stations,” *in Proc. of ACM MobiCom*, pp. 53–64, 2012.

Your Comment: No performance comparison is provided. Thus, the reviewer cannot judge the superiority of the developed scheme.

Our Response: We understood the importance of performance comparison to show the superiority of our design. Unfortunately, in the literature, there is no spectrum sharing scheme that we can use as the benchmark for performance comparison. This is because there is no technique in the literature that can be used for a secondary receiver to decode its desired packets in the presence of unknown interference. For this reason, the existing spectrum sharing schemes in the literature are limited to either theoretical exploration or practical design in cooperative networks. To the best of our knowledge, our work, along with our demo system, represents the first solution enabling real-time concurrent spectrum utilization for heterogeneous wireless networks in the absence of cross-network coordination and inter-network knowledge (e.g., waveform and frame format).

Demo video: `http://www.ece.louisville.edu/hzeng/spectrum_sharing.html`

Your Comment: The developed MAC protocol is very basic and the reviewer cannot find sufficient novelty from the designed protocol.

Our Response: The contribution of this work does not lie in the design of MAC protocol, nor do we claim the novelty of the MAC protocol in the manuscript. The contribution of this work lies in the design of BIC and BBF techniques at the PHY layer as well as the system implementation and validation.

We re-state our contributions on page 2 of the revised manuscript. We copy it below for your review.

“ This paper advances the state-of-the-art in the following aspects: i) We have designed a new BIC for a wireless receiver, which can decode its data packets in the presence of unknown interference. In addition to its application in CRNs, it has many other applications in wireless networks, such as securing wireless communications against radio jamming attacks and enhancing Wi-Fi reliability in the face of unknown co-channel interference. We have implemented such a wireless receiver on a wireless testbed and demonstrated that it can work in real time in real-world wireless environments. Our experimental results show that it achieves about 33 dB cancellation for unknown interference. ii) We have proposed a new BBF technique for wireless transmitter, which can pre-cancel its generated interference for an unintended receiver. Particularly, this BBF technique does not need to have channel information for beamforming; instead, it uses overheard unknown interference for beamforming filter design. We have implemented the proposed BBF on a wireless testbed and demonstrated that it achieves 25 dB pre-cancellation for the unintended receiver. iii) To the best of our knowledge, this work is the first one that demonstrates real-time concurrent spectrum utilization of two real-world wireless systems in the absence of collaboration.”

Response to Reviewer 4's Comments

Your Comment: The paper addresses the relevant topic of practical underlay spectrum sharing and provides both the theoretical foundation and experimental evaluation in a real deployment environment. The research contributes to the challenging, yet highly relevant case of the secondary user being fully responsible not to interfere with the primary user, without cooperation from the primary user. The authors leverage advanced wireless technology, which makes their solution practical and interesting for researchers and developers. The paper is well written and provides enough details about the research. Please consider my suggestions, which are mostly of editorial nature

Our Response: Thank you very much for your review and constructive comments, which helped us improve the quality of this work. In this revision, we have carefully studied your comments and revised our manuscript based on your suggestions. The revised parts are highlighted in blue color. The detailed point-by-point responses are provided below.

Your Comment: Consider including the following theoretical paper as a recent contribution along [3]-[8] in the third paragraph of the introduction. It will foster the significance of your work. The paper is published in IEEE GLOBECOM 2019.

Our Response: Thank you for providing this reference. We have added this reference in the revised manuscript (on page 1).

[Ref-3] R. M. Rao, H. S. Dhillon, V. Marojevic and J. H. Reed, "Analysis of worst-case interference in underlay radar-massive MIMO spectrum sharing scenarios," 2019 IEEE Global Communications Conference (GLOBECOM), Waikoloa, HI, USA, 2019, pp. 1-6.

Your Comment: Please consider my suggestions, which are mostly of editorial nature:

- 'a crucial problem' –> important
- 'from that primary user.' –> from the primary user transmitter.
- 'channel knowledge or inter-network synchronization' –> ... nor ...
- 'embedded in data frame' –> embedded in the data frame of the primary user
- 'There is some pioneering work' –> There are some pioneering works
- 'pre-cancel its generated interference for the primary receiver' –> pre-cancel interference from its own transmission at the primary receiver
- Objective (iv): you could add '...in a real indoor setting.' or '...in an office environment.'
- 'over the time' –> over time
- 'noises' –> noise

Our Response: Thank you very much for your careful review. We have revised the manuscript based on your suggestions. We have also thoroughly proofread the manuscript to ensure that it has no other typos.

Your Comment: Can you provide more information about your LTE-like primary network? Specifically, comment on the sampling rate, signal bandwidth, signal power, and what reference signal (pilot) configuration you assume. LTE uses diamond-shaped reference signal distribution and specific sampling rates.

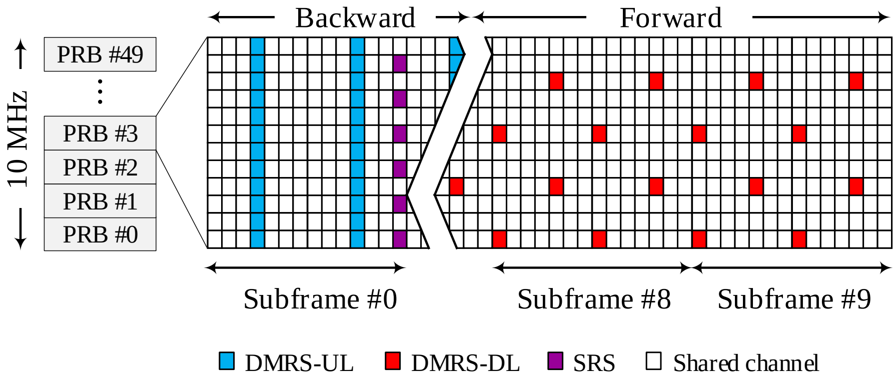


Figure 9: The frame structure used by primary users in primary network 2 with LTE-like PHY.

Our Response: Fig. 9 illustrates the frame structure used by the primary network in our experiments. As shown in the figure, the downlink reference signal configuration in LTE is used for forward transmissions (form PU 1 to PU 2) and uplink reference signal configuration for backward transmissions (from PU 2 to PU 1). An LTE-like frame lasts for 10 ms and includes 10 subframes. One subframe comprises 14 OFDM symbols. Also, the frame has 50 resource blocks, each of which comprises 12 subcarriers. Therefore, the number of valid subcarriers is 600, and we use 1024 points for FFT operation. The sampling rate employed by the primary network 2 is 10 Msps and the effective bandwidth of signals transmitted by primary users is 5.859 MHz. The PHY specification of primary network 2 has been provided in Table I of the revised manuscript.

Your Comment: In the conclusions you mention USRP2, which is an early USRP model and different from the N210. A picture of your testbed would be nice to include.

Our Response: Thank you for your suggestion. We used USRP N210 devices in our experiments. We have revised the conclusion section to remove the confusion. Moreover, we have added the picture of our testbed to Fig. 9 of the revised manuscript. For your convenience, the picture is presented in Fig. 10 for your review.

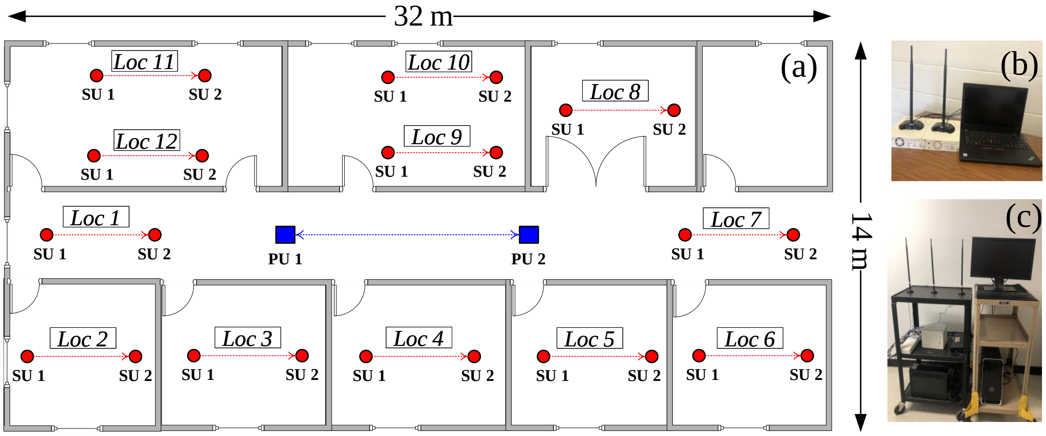


Figure 10: Experimental setting: (a) floor plan of primary and secondary users' locations; (b) a secondary transceiver; and (c) a primary transceiver.