SpaceHub: A Smart Relay System for Smart Home

Meng Meng[1,2] *, Lizhao You[1,3] *, Kun Tan[1], Jiansong Zhang[1], Wenjie Wang[2]
[1]Microsoft Research Asia, Beijing, China
[2]Xi'an Jiaotong University, Xi'an, China
[3]The Chinese University of Hong Kong, Hong Kong, China
{v-memeng,kuntan,jiazhang}@microsoft.com,yl013@ie.cuhk.edu.hk,wjwang@xjtu.edu.cn

ABSTRACT

With the proliferation of smart wireless devices in our homes, the cross-technology interference increasingly becomes an important issue. This paper presents a novel smart relay system, called SpaceHub, which leverages an multi-antenna relay node to mitigate cross-technology interference for all communicating devices which may only have single antenna. In SpaceHub, the relay node overhears wireless communications in the air, separates the collided signals, and forwards the separated (cleaned) signals to their intended receivers without a prior knowledge of the wireless signal structures. The core component of SpaceHub is a blind signal separator that constructs spatial filters using the angle-of-arrival information of collided signals. We have implemented SpaceHub on a software radio platform and our evaluation shows SpaceHub signal separator can suppress the interference up to 23dB, and is robust against the power or relative locations of interfering signals.

Categories and Subject Descriptors

C.2.1 [**Computer Communication Networks**]: Network Architecture and Design–Wireless communication

Keywords

Relay; Antenna Array; Spatial Filter; Internet of Things

1. INTRODUCTION

Over last few years, we have witnessed a proliferation of wireless technologies that increasingly become ubiquitous in our everyday life. With this global wave of Internet-of-Things (IoT), more and more intelligent devices are deployed in our home and interconnected with many heterogeneous wireless technologies. However, most of these wireless technologies are crowded in the same unlicensed frequency bands. For example, Wi-Fi, ZigBee, Bluetooth, Digital cordless phone, and many other proprietary wireless technologies for surveillance camera or remote controller, all operate on the same 2.4GHz ISM band. Consequently, interference among these wireless technologies may result in unreliable communication or low network throughput.

Some conventional coexisting technologies try to add more redundancy [5] to tolerate more interference. Some other technologies manage to avoid interference by scheduling transmissions over different channels [11,12] or time slots [4,13]. However, these solutions are not very effective. Adding redundancy reduces the communication data rate and thus sacrifices the spectrum efficiency. At the same time, the scheduling based solutions essentially divide the limited wireless capacity to each user. The throughput of each user will drop with increasing number of competitors.

Recently, several research has explored to use MIMO capability to handle cross-technology interference [2,10]. These solutions require one or both communication side(s) to equip multiple antennas and use a portion of degree-of-freedom (DoF) to nullify interference. However, as adding multiple antennas significantly adds device size, cost and power consumption, none of them could support all wireless communications inside a smart home, where many IoT devices are just small sensors and embedded actuators and infeasible to add multiple antennas.

In this paper, we present a novel system, named SpaceHub, that utilizes MIMO technologies to mitigate cross-technology interference even if all communicating devices have only single antenna. Our idea is to deploy a multi-antenna relay that overhears wireless communications in the air, separates the collided signals if any, and forwards the separated (cleaned) signals to their intended receivers.

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One primary design goal of SpaceHub is to be *wireless technology agnostic*, which can enable following nice properties: First, the existing wireless devices can be easily configured to work with SpaceHub. Neither the hardware structure nor the physical layer setting of the device needs to be modified. Second, SpaceHub can help any emerging wireless technology without a priori knowledge of its physical/MAC layer design. Finally, SpaceHub improves the spectrum efficiency of all wireless technologies with spatial multiplexing even if all communicating devices are only with single antenna.

Being wireless technology agnostic is not trivial. Conventional MIMO systems need to measure the wireless channel coefficients from known symbol structures (e.g., preambles), and these channel coefficients are critical to separate mixed signals. However, for SpaceHub, it is infeasible to perform such measurements as the wireless signals in question are unknown. To this end, one core technique in SpaceHub is a *blind signal separator* that can reliably separate multiple spatial streams without a priori knowledge of the signal structure. Our signal separator is motivated by the Angle-of-Arrival (AoA) detection mechanism used in wireless localization systems [3,9]. But unlike previous work, SpaceHub utilizes this AoA information to construct a set of spatial filters to separate signals arrived from different directions. Further, SpaceHub identifies the multi-path reflections from a same source and combine them to enhance the signal strength. Finally, with a proper antenna placement and a cancellation technique, SpaceHub can also separate signals from different sources even if they are coming along close directions.

We have implemented SpaceHub on Sora MIMO kit. Evaluation results show our separation algorithm could improve the SINR of collided signal by an average of 15dB (up to 23dB). The signal separator is robust against the interference signal strength as well as the relative locations of interfering sources – even the signals arriving from the same direction can be precisely separated. Finally, We also observe about 4dB SINR improvement to combine multipath components of one signal source from several different directions.

In summary, our contributions are: 1) To our best knowledge, SpaceHub is the first smart wireless relay system that uses multi-antenna technology to mitigate cross-technology wireless interference and separate collided signals. 2) We design a novel blind signal separator. 3) We implement and evaluate SpaceHub on a software radio platform.

2. BACKGROUND

2.1 MIMO Primer

Conventionally, a 2 × 2 MIMO system works as follows. Two transmit antennas send signal $s_1(t)$ and $s_2(t)$ respectively, then the received signals on each receiver antenna can be expressed as

$$\begin{aligned} x_1(t) &= h_{11}s_1(t) + h_{12}s_2(t) \\ x_2(t) &= h_{21}s_1(t) + h_{22}s_2(t) \end{aligned}$$

where h_{ik} represents the channel coefficient from transmit antenna k to receiver antenna i.

If the receiver knows the channel coefficient h_{ik}, it can separate the two unknown signals, *i.e.*, $s_1(t)$ and $s_2(t)$, by solving the above equations. In a conventional MIMO system, to estimate h_{ik}, the transmitter needs to send a training signal (*i.e.*, preamble) that is known to the receiver in advance.

Unfortunately, in SpaceHub, we cannot assume that the signal structure is always available (*i.e.*, being wireless technology agnostic). As a consequence, we cannot acquire channel coefficients through such measurements. To address this challenge, we observe that signals from different sources may be distinguished through their spatial locations. Essentially, we can design a spatial filter which can only receive the signal from an interested direction but attenuate all signals from other directions.

2.2 AoA Estimation

The basic idea in SpaceHub is to utilize the difference in angles of arriving (AoA) from multiple transmitters to separate the concurrent signal streams. Therefore, AoA estimation is a basic component of the SpaceHub. In the following, we introduce the widely used MUSIC algorithm [6] which is employed in our design.

Consider a simple case in Fig.1. There is a receiver with M antennas evenly spaced on a straight line. The antenna separation is $\lambda/2$ (half-wavelength).Two signal sources are placed far apart, and the distances from each source to the first antenna of AP are d_1 and d_2, respectively. The signal from each source has a line-of-sight path to the AP antenna array, with attenuations a_1 and a_2 and angles of incidence θ_1 and θ_2.

Assume that $x_i(t)$ is the received signal at i^{th} antenna at time t, we get the receiver vector $X(t)$

$$\begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_M(t) \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ e^{-j\pi cos\theta_1} & e^{-j\pi cos\theta_2} \\ \vdots & \vdots \\ e^{-j(M-1)\pi cos\theta_1} & e^{-j(M-1)\pi cos\theta_2} \end{bmatrix}$$

$$\begin{bmatrix} a_1 e^{-\frac{j2\pi d_1}{\lambda}} & 0 \\ 0 & a_2 e^{-\frac{j2\pi d_2}{\lambda}} \end{bmatrix} \begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ n_2(t) \\ \vdots \\ n_M(t) \end{bmatrix} \qquad (1)$$

If we define array steering vector $a(\theta)$ as

$$a(\theta) = [1 \; e^{-j\pi cos\theta} \ldots \; e^{-j(M-1)\pi cos\theta}]^T \qquad (2)$$

we can see that the value of $a(\theta)$ only depends on the incoming signal's direction.

MUSIC algorithm exploits the eigenspace of data's covariance matrix $R_x = \mathbb{E}\{XX^H\}$, where $(.)^H$ represents the Hermitian of a vector(the conjugate transpose). Assuming the incident signals are uncorrelated to noise, MUSIC splits the eigenspace of R into signal-subspace and noise-subspace. While the eigenvectors U_s corresponding to the largest D eigenvalues span the signal-subspace, the remaining $M - D$ eigenvectors U_n span the orthogonal space, saying noise-subspace. Note that all array steering vectors $a(\theta)$ which describe D signals, are orthogonal to the noise-subspace.

Thus, MUSIC plots the spatial spectrum as

$$P_{MUSIC}(\theta) = \frac{1}{a^H(\theta)U_n U_n^H a(\theta)} \tag{3}$$

when θ is a signal direction, the denominator becomes zero and yields a sharp peak in the spatial spectrum.

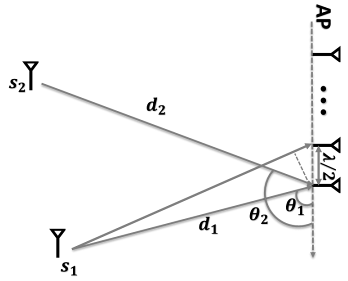

Figure 1: Two geographically separated signal sources to a receiver antenna array.

3. SpaceHub ARCHITECTURE

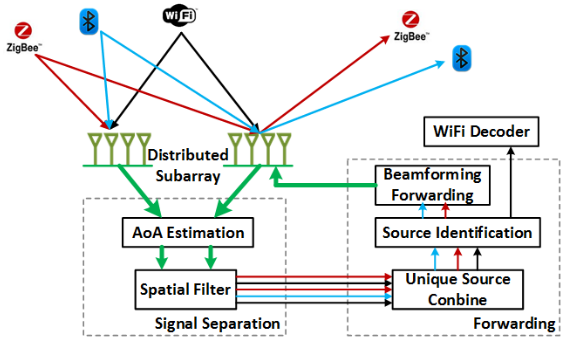

Figure 2: SpaceHub overview.

SpaceHub leverages a MIMO relay node to separate and forward collided signals from multiple wireless transmitters. Commonly, this MIMO relay can be integrated together into a Wi-Fi access point (AP), as shown in Fig. 2.

SpaceHub keeps monitoring the wireless medium, and employs a blind signal separation technique onto the received signals. The signal separation starts from the AoA estimation, where SpaceHub searches the spatial spectrum and finds directions of all incoming signals. Then, for each direction in which a signal is detected, SpaceHub constructs a *Spatial Filter* to steer the antenna array to amplify the signal from this direction, but attenuate signals from other directions. After extracting signals from all directions, SpaceHub further clusters these signals into groups, so that each group contains multi-path components from a same sender. These multi-path components may come from different directions (due to reflections), but should be combined together to reconstruct the original wireless signal. Clearly, if SpaceHub finds more than one group, there is a collision.

After all signals are separated (and combined), SpaceHub relays them to their intended receivers. In this paper, since SpaceHub is integrated with a Wi-Fi AP, it will first detects Wi-Fi signals according to the physical layer features. All Wi-Fi signals are just fed to local decoder (Fig 2), but other signals are amplified and forwarded to their destinations.

There can be two possible ways to forward signals. Firstly, SpaceHub can directly broadcast all relay signals one by one. But this will take n time slots to n packets in a collided transmission. Alternatively, SpaceHub could leverage its multi-antenna capability to forward multiple signals simultaneously using beamforming. In §4.2, we will discuss how to enable this beamforming forward, but leave the implementation and detailed evaluation as our future work.

There are also two points worth noting. First, the AoA method has a fundamental limitation to distinguish different signals from the same direction. Therefore, if two wireless devices are aligned in the same direction with respect to SpaceHub's antenna array, SpaceHub may not be able to separate their collided signals. We address this issue by augmenting SpaceHub with a second antenna array and an intelligent cancellation algorithm (§4.1). Second, the relay behavior of SpaceHub will interact with some existing MAC protocols. For example, Wi-Fi requires the receiver to send a synchronous ACK after receiving a data packet without performing carrier-sensing. This synchronous may collide into other on-going relay transmissions of SpaceHub. To remedy this, we need slightly modifications on these MAC protocols to sense wireless channel for ACK packets as well[1]. This is similar to previous work [14, 15] that requires MAC to be relay friendly. We note that ACK-to-ACK collision may not be an issue here as SpaceHub can help to separate and forward ACK packets as well. However, a complete MAC design is defered as our future work.

4. SpaceHub DESIGN

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[1] The ACK timeout mechanism at the sider side may also need to modify slightly to accommodate the increased delay in ACK.

4.1 Blind Signal Separation

Recall that SpaceHub uses a spatial filter to separate signals from different directions. The spatial filter is to steer the array's beam pattern in one direction by forming a linear combination of the antenna outputs

$$\hat{s}_k(t) = \sum_{n=0}^{M-1} w_n^* x_n(t) = W^H X \tag{4}$$

For our separation purpose, the spatial filter should be able to suppress other signals (i.e., interfering sources) as much as possible. We adopt an optimal filter that maximizes signal to noise plus interference ratio (SINR).

Assume the desired signal $s_0(t)$ is from direction $a(\theta_0)$, and $s_k(t)(k = 1, \cdots, D-1)$ represents other signals considered as interference sources. The optimal weight is $W_{opt} = \gamma R_u^{-1} a(\theta_0)$, where R_u is the covariance matrix of noise and interference, and $\gamma = \frac{1}{a^H(\theta_0) R_u^{-1} a(\theta_0)}$ is a constant scale.

However, applying above filter is not enough to extract each unique signal from collision signals. We will present further processing in the following sections.

4.1.1 Multipath Identification and Combination

Some separated signal streams may contain multipath components from the same transmitter. Simply forwarding all of them is clearly a waste of resource (e.g., time slots). Instead, in SpaceHub, we combine each signal stream's multipath components to enhance the source signal.

Identification: Before combination, SpaceHub needs to first identify the source of each separated signal stream. The core idea is that all separated signal copies from one unique source should show a strong correlation, whereas signal streams from different sources are uncorrelated. Therefore, SpaceHub clusters all the separated signal streams into several groups according to their cross correlation. Each group is considered as multipath components of a single source, and then combined into a single signal stream. However, a problem may occur when a separated signal contains components from two distinct sources (combined copy), i.e., two sources are in the same direction for SpaceHub. In this case, this combined copy will be identified as a path of two signals by mistake. We will discuss how to further differentiate a combine copy from a pure signal in Sec.4.1.2.

Combination: We use a maximal ratio combination algorithm to combine the multipath components. Considering a signal $s_1(t)$ which propagates along two paths before arriving at the antenna array, after separation we obtain two copies $y_1(t) = a_1 e^{-\frac{j2\pi d_1}{\lambda}} s_1(t)$ and $y_2(t) = a_2 e^{-\frac{j2\pi d_2}{\lambda}} s_1(t)$, where a_1 and a_2 are real number scalars. Their cross correlation is

$$\begin{aligned} R_{12}(\tau) &= \mathbb{E}\{y_1^*(t) y_2(t+\tau)\} \\ &= a_1 a_2 e^{\frac{j2\pi(d_2-d_1)}{\lambda}} \mathbb{E}\{y_1^*(t) y_1(t+\tau)\} \end{aligned} \tag{5}$$

let $\tau = 0$, the phase offset $\Delta\beta$ can be estimated by $\arctan R_{12}(0)$. Then the signal after maximal ratio combination is

$$\widehat{s_1}(t) = s_1(t) + e^{j\Delta\beta} s_2(t) \tag{6}$$

4.1.2 Signal Separation from Same Direction

Since the spatial filter extracts signals based on AoA difference, it has an inherent limitation to differentiate signals coming from the same direction.

In SpaceHub, we leverage multiple phase arrays to further separate independent signals from one direction. The intuition is that, the AoA profiles vary from one location to another. The signals mixed in the AoA profiles in one phase array may be separable in the profile of another array with high probability. SpaceHub jointly processes the signals from two separate phase array antennas to reduce the occurrence of inseparable signals.

To illustrate our algorithm, let us consider two phase arrays and two sources in the same direction. For phase array P, assume the signal copy $y_1(t)$ separated from angle θ_i^1 is a combined signal of source $s_1(t)$ and $s_2(t)$. For phase array P', the best case is that we can separate the two pure signal copies $s_1(t)$ and $s_2(t)$ respectively. If so, we can just discard this combined signal copy at array P. However, in some cases, we may just obtain one pure $s_1(t)$ but another signal, $s_2(t)$, may be combined with another different source. Assume $y_1'(t)$ is the sole signal $s_1(t)$ from angle θ_i^2. In this way, the received signals can be written as

$$\begin{aligned} y_1(t) &= \alpha_1 s_1(t) + \alpha_2 s_2(t) + n_1 \\ y_1'(t) &= \alpha_3 s_1(t) + n_2 \end{aligned}$$

where $\alpha_i (i = 1, 2, 3)$ denotes the remaining complex scalar after spatial filter, which are unknown.

Cancellation: We exploit the independence of $s_1(t)$ and $s_2(t)$ to obtain $s_2(t)$ from combined signal copy $y_1(t)$. Specifically, we can compute a complex scalar h such that $y_1(t) - h y_1'(t)$ is uncorrelated with $y_1'(t)$. Therefore, we can have $\mathbb{E}\{(y_1(t) - h y_1'(t)) y_1'(t)\} = 0$. That is

$$h = \frac{\mathbb{E}\{y_1(t) y_1'(t)\}}{\mathbb{E}\{y_1'(t) y_1'(t)\}} \tag{7}$$

and the relay can obtain the forwarding signal $\widehat{s_2}(t) = y_1(t) - h y_1'(t)$.

Identification: Another question is how SpaceHub knows $y_1(t)$ is the combined signal copy of $s_1(t)$ and $s_2(t)$. Similar to the identification of multipath signals, SpaceHub applies a preprocessing algorithm to cluster signal copies based on cross correlation results. In particular, SpaceHub identifies the combined copy from the pure one based on the following observation: For signal copy $y_k(t)$ obtained from phase array P, all the signals from phase array P' coherent with $y_k(t)$ form a group $G'(k) = \{y'_i(t)|i = 1, 2...\}$. $y_k(t)$ is a combined copy if and only if there exist two signal copies within y'_i uncorrelated with each other.

Then, SpaceHub clusters all pure copies from one phase array into several groups by their correlation relationships as discussed in Sec. 4.1.1.

4.2 Beamforming Forwarding

We briefly discuss simultaneous signal forwarding using beamforming. To achieve beamforming, we need to address following two practical issues.

First, we need to figure out the destination of a signal stream. It is not straightforward as the signal structure is not available, and therefore we will not be able to identify the destination by decoding the MAC address. However, we still can leverage several wireless properties to design a learning scheme. For example, as signal streams from different wireless technologies have distinct physical layer patterns, SpaceHub can classify signal streams into different groups according to their physical layer features. Moreover, since many wireless technologies require ACK from receivers, this MAC behavior can be utilized to link a source device to a destination device. Once it needs to forward a signal from source i, it will find all devices connected to source i, and beamform the signal to all these devices. The signal's intended destination will receive this packet, and other receivers will reject it.

Second, we need a new precoding technique that does not require channel coefficients. Again, it is due to the fact SpaceHub is wireless technology agnostic. However, we can reconstruct the precoding filter using AoA information similar to the separation filter. We defer this beamforming forwarding as our future work.

5. EVALUATION

We implement SpaceHub on latest Sora MIMO kits [7]. There are total 14 antennas[2] that are connected to a back-end server through Ethernet. These antennas form two phase subarrays. The distance between two subarrays is about 1 meter. The distance between two antennas in each subarray is 6 centimeters. We adopt a trace-driven approach to evaluate the separation performance in this section.

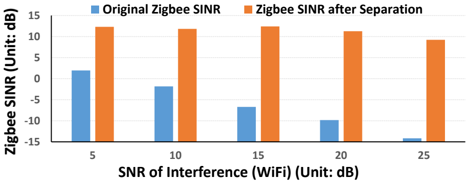
5.1 Spatial Filter

Method: A Wi-Fi device and a Zigbee device are placed around the antenna array, and are activated to send packets periodically on an overlapped channel (i.e., channel 9 for Wi-Fi, and channel 20 for Zigbee). We choose Zigbee signal as the test signal, and choose Wi-Fi signal as the interference. We measure the SINR of Zigbee signal as $\frac{E_{zigbee}}{E_{wifi}+E_n}$, where E_{zigbee} and E_{wifi} are Zigbee and Wi-Fi signal power, and E_n is the noise.

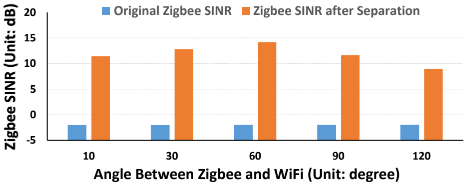
To compute the original Zigbee SINR before separation, we let Wi-Fi and Zigbee send their signals alone, and measure E_{zigbee}, E_{wifi} and E_n directly. To compute the Zigbee SINR after separation, we let Wi-Fi and Zigbee transmit simultaneously, and apply the spatial filter defined in Sec. 4.1 to get the overall power $E_{S.I.N}$. Then, we silence Zigbee signal, and apply the same filter to get the interference plus noise power $E_{I.N}$.

We conduct two sets of experiments. First, we fix the angle between two devices, and vary the transmission power of Wi-Fi from 5dB to 25dB. For each case, we capture 5 traces and each trace contains around 100ms signal. From these received packets, we pick up 8 collision packets for signal separation and SINR evaluation. Second, we fix the transmission power of Wi-Fi at 10dB, and vary the angle between two devices from 10° to 120°. For each angle, we do similar measurements as above. In both experiments, the Zigbee SNR is 10dB.

Results: The results are shown in Fig. 3. We can see that the original Zigbee SINR shows a sharp reduction along with increasing interfering power in Fig. 3(a). However, our separation algorithm restores the signal SINR to around 10dB, although the SINR decreases slightly as the interference increases. Meanwhile, Fig. 3(b) shows our separation also works for various angles. The restored SINR is around 10dB. These results indicate that our separation algorithm is robust again interfering power and angles.



(a) Vary interfer power



(b) Vary devices angle

Figure 3: The SINR comparision of Zigbee

5.2 Multipath Identification Accuracy

Method: We place Wi-Fi and Zigbee devices randomly in 9 different locations. For each location, they

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[2] With four Sora MIMO kits, we can equip 16 antennas in total. However, for each phase array, we need a special radio to calibrate initial phase. So the number of antennas constituted in each phase array is 7.

send packets periodically with random SNR values. When Zigbee keeps silent, we record the arriving angles of separated signal copies as ground truth of Wi-Fi's multipath. Similarly, we can record the ground truth of Zigbee's multipath. If two devices locate in the same direction for any one subarray, we record this direction as ground truth of combined signal copy.

We use the following metrics to evaluate the performance of identification accuracy: 1) False positive: it measures the probability that SpaceHub incorrectly alarms the presence of a path in one direction. 2) False negative: it measures the probability that SpaceHub fails to detect the presence of a path in one direction.

Results: Table 1 shows that our algorithm has a super low False Negative Rate of multipath identification, which implies it achieves an average identification accuracy rate of 99%. Overall, it performs well in identifying signal copies, which is the basis for further multipath combination and signal separation from same direction.

Signal Type	False Positive	False Negative
Wi-Fi	0.030	0.008
Zigbee	0.018	0.010
Combined Signal	0.028	0

Table 1: Multipath Identification Accuracy.

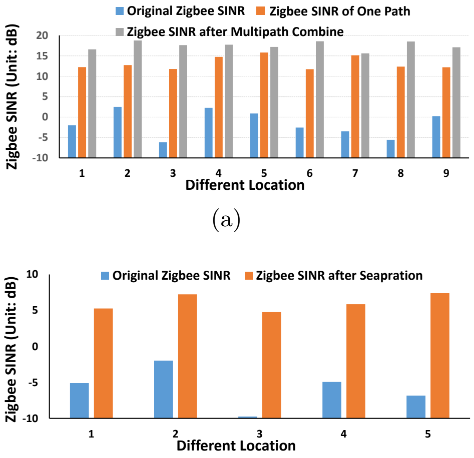
5.3 Multipath Combination and Signal Separation from Same Direction

Multipath Combination: Based on the traces captured in section 5.2, we measure the Zigbee SINR before separation, SINR of direct path and SINR after combination for 9 different locations. As shown in Fig. 4(a), multipath combination can enhance signal SINR on average by about 4dB.

Signal Separation from Same Direction: We place Wi-Fi and Zigbee devices in 5 different locations. For each location, they locate in a line for one subarray. We measure the SINR increase of Zigbee signal as before, and plot the evaluation results in Fig. 4(b). We can see that even though two signal sources arrive at one subarray from the same angle, our system can still separate them, and improve the SINR after separation.

6. RELATED WORK

Cross-technology Interference: Cross-technology interference increasingly becomes severe with the proliferation of wireless technologies. Literatures have tried to address the problem in different ways. Several methods [11, 12] are proposed to dynamically switch to an unused channel based on spectrum sensing, while some other approaches [4, 13] are based on time scheduling or traffic control. Besides, Ref. [5] adds coding redundancy to protect Zigbee packets from Wi-Fi interference. Recent research works [2,10] utilize the MIMO technology to protect Wi-Fi or Zigbee communications in the presence of RF interference. Instead, SpaceHub mitigates the RF interference for all the wireless technologies irrespective of their physical/MAC layer design.



(a)

(b)

Figure 4: The SINR comparison of Zigbee in different locations.

AoA Estimation and Adaptive Beamforming: AoA estimation has been applied in wireless localization systems like ArrayTrack [9], PinPoint [3]. SpaceHub is motivated by these works, but we target at smart relay system to mitigate wireless interference. SpaceHub is also inspired by previous adaptive beamforming work in smart antenna field [1, 8]. Unlike traditional adaptive beamforming which enhances receive SNR of one intended signal, SpaceHub exploits its spatial filter design to separate collided signal. Additionally, SpaceHub develops a multipath identification mechanism to combine multiple reflections of the same source using maximal ratio combination to enhance the signal strength.

7. CONCLUSION AND FUTURE WORK

This paper presents SpaceHub that leverages a multi-antenna relay node to mitigate cross-technology interference for all communication devices even if all of them have only single antenna. The core of SpaceHub is a blind signal separator which can separate collided signals without a prior knowledge of the wireless signal structures. We have implemented SpaceHub on latest Sora MIMO kit and evaluate it performance. One immediate future work of SpaceHub is to enable simultaneous forwarding of multiple heterogeneous signals through beamforming. This will greatly reduce the duration of the forwarding phase in SpaceHub. Besides, we will also design a more comprehensive MAC protocol to allow other devices to leverage SpaceHub relay better to improve the overall performance.

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