Increasing Cellular Capacity Using ISM Band Side-channels: A First Study

Jingwen Bai
Rice University
Houston, TX, USA
jingwen@rice.edu

Chenxi Liu
Tsinghua University
Beijing, China
chenxi_liu@live.cn

Ashutosh Sabharwal
Rice University
Houston, TX, USA
ashu@rice.edu

ABSTRACT

The rise of ISM band radios, notably for WiFi, with near-default inclusion in smartphones, has been phenomenal. The use of ISM band radios is largely controlled by end-users for data access, either directly connecting to a WiFi access point or wireless tethering. We study an additional use of ISM bands to manage interference in cellular bands, by creating ISM "side-channels" between mobile clients. Our objective is to increase the network capacity in cellular bands, when there is no opportunity of data offloading to WiFi. We first study the likelihood of finding a WiFi-free environment, specifically on highways, to establish an ISM side-channel between smartphones. The likelihood is found by experimentally studying the range of WiFi links between smartphones with our designed Android applications, combined with rush hour traffic data on highways; the result is that there is high probability of finding at least one smartphone within the ISM band range. Finally, we show that the proposed use of ISM side-channels can significantly reduce interference in a MIMO wireless system and increase the overall cellular network capacity, by flexibly accommodating both multiuser beam-forming and full-duplex operation.

Categories and Subject Descriptors

C.2.0 [**Computer Systems Organization**]: Computer-Communication Networks–General

Keywords

ISM side-channels; Interference management; Device-to-device communication; Capacity

1. INTRODUCTION

Almost all smartphones today can *simultaneously* operate in two orthogonal frequency bands, i.e. ISM and cellular bands. The ISM bands are commonly used by WiFi and Bluetooth, and the cellular bands for cellular voice and data. The simultaneous operation in two orthogonal bands has been used for many purposes. For example, data offloading to WiFi networks is a common method to reduce cellular congestion. Or simultaneous operation is used to support wireless tethering, which allows devices to share one cellular link over WiFi. While WiFi infrastructure is considered "ubiquitous" in metropolitan areas, the truth is that its deployment is limited to very low mobility environments; most common WiFi covered zones include homes, offices, malls and restaurants. Due to its short-range and limited support for handoffs in high mobility scenarios, large outdoor swaths of cities may have limited, very weak or no WiFi coverage. We focus on the areas where WiFi coverage is practically unavailable.

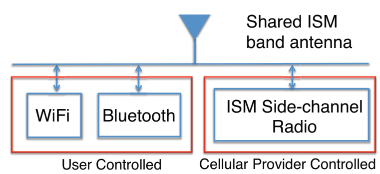

Figure 1: The proposed use of ISM side-channel, as an additional radio to access ISM bands when available and controlled by cellular providers.

In this paper, we propose and study the potential for an additional use of ISM bands to create *side-channels* for interference management to increase the overall cellular network capacity. The proposed use is neither data-offloading nor data-forwarding. The side-channels are established between mobile clients and *controlled* by the cellular provider in only WiFi-free zones, and used to manage intra-cell interference in advanced MU-MIMO techniques; see Figure 1. We understand that our model of cellular controlled ISM bands appears to be problematic at first, since ISM channel use has always been under the control of end-users. We expect that users will still have the highest priority to control ISM band (e.g. for WiFi or tethering). Our proposed solution will only be active when the user has no use of the ISM band and opts in to allow cellular providers to manage the use of the ISM side-channels for improved capacity for the client.[1]

We will leverage the ISM side-channels among mobile clients to boost data rate of cellular transmissions by *improved intra-cell interference management*. We will consider the advanced upcoming techniques like multiuser MIMO (MU-

[1]Our focus is only on capacity improvement in this paper, and many important issues like energy efficiency and security will be addressed in future work.

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MIMO) and full-duplex communication as our examples for the use of ISM side-channels. In both MU-MIMO and full-duplex, multiple flows are active in the *same* cell, which leads to intra-cell interference as shown in Figure 2.

Our main findings are two-fold. First, we quantify the opportunities of using ISM side-channels among smartphones in WiFi-free area such as highways. Using our designed Android applications, we measure WiFi link quality between two smartphones either placed within one vehicle, or in separate vehicles. The measurements provide an estimate on the range of ISM band links between smartphones. We find that up to a distance of 50 meters, we can obtain an average received power greater than -80 dBm.[2] Combining with highway traffic data accessible in California, we derive an estimate on the probability of establishing ISM side-channels on highways during rush hour. We find that during rush hour, there is a 69% chance for an ISM side-channel to exist within 50 meters on highways with reliable link quality.

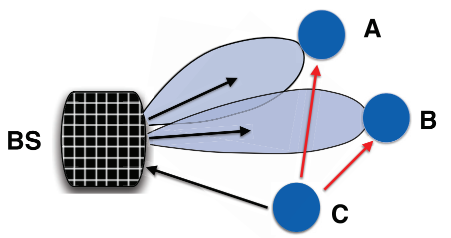

Figure 2: In a MU-MIMO full-duplex system with half-duplex mobiles, there is inter-beam interference among the downlink users (for example, between A and B) and uplink-downlink interference (for example, from C to A and B).

Second, we analyze information-theoretic cellular capacity increase with ISM side-channels in the future advanced wireless systems. Recent results on experimental evaluation of MU-MIMO [11] and full-duplex infrastructure for short to medium range communication [4, 5] demonstrate the potential significant improvement on spectral efficiencies over all previous existing wireless architecture. However, one detrimental factor which limits the performance of such architecture is the intra-cell interference among the users in the same cell. For instance, in the MU-MIMO downlink, serving multiple downlink users simultaneously via transmit beamforming techniques [12] will incur inter-beam interference owing to the imperfect channel state information at the transmitter. On full-duplex base stations, there is a potential to schedule the up- and downlink pairs in the same resource block, hence the uplink stream may interfere with the downlink stream especially in a dense environment. In Figure 2, we show that in MU-MIMO full-duplex system, there is inter-beam interference between downlink user A and B, and uplink-downlink interference from uplink user C to downlink users A and B.

We demonstrate that with ISM side-channels, we can leverage recent techniques like decode-and-cancel [2] and user-cooperation [10] to manage intra-cell interference. The capacity loss due to intra-cell interference can be completely recovered by exploiting the ISM side-channels among users. The simulation results based on our WiFi channel measurements show that with 20 antennas at the base station, our MU-MIMO full-duplex system via ISM side-channels will increase the capacity of MU-MIMO half-duplex downlink by 6-fold and TDMA by 12-fold, and recover the full-duplex multiplexing gain which previous schemes without ISM side-channels fail to achieve.

The rest of the paper is organized as follows. In Section 2, we compute an estimate on the likelihood of finding another smartphone within ISM band communication range during rush hours on highways. In Section 3, we compute the potential increase in capacity due to ISM side-channels, and conclude in Section 4.

2. AVAILABILITY OF ISM SIDE-CHANNELS

In this section, we estimate the likelihood of establishing ISM side-channels among smartphone users, in places where there is no WiFi coverage such as highways. In highways, as shown in Figure 3, there are two different types of opportunities to establish ISM side-channels: intra-vehicle where the smartphones are in the same vehicle and inter-vehicle where the smartphones are placed in separate vehicles.

We first measure the channel strength of WiFi links between smartphones in both intra- and inter-vehicle environments. We use WiFi as a proxy for this future ISM side-channel only for link quality measurements, since it is the only easily accessible radio available in ISM band embedded in the form-factor device of the envisioned use.[3] The measurement data provides us with estimates on the range of WiFi links between smartphones possible in highways. Then we use the highway traffic data, combined with our range tests, to estimate the number of times two smartphones can be within each other's ISM band communication range.

We note that several experiments have been reported for vehicle-to-vehicle dedicated short-range communication (DSRC) in [9]. However, DSRC measurements are often performed to mimic vehicle mounted transceivers and antennas, which are potentially more capable than smartphone radios and antennas. To get a more realistic smartphone-to-smartphone link range estimate, we chose to perform our own independent tests using current WiFi hardware in smartphones.

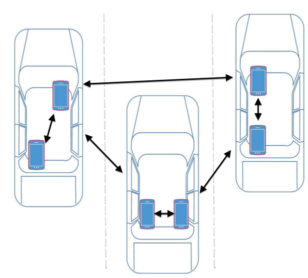

Figure 3: Intra-vehicle and inter-vehicle ISM side-channels among clients.

2.1 Methodology

Two Android smartphones (HTC One M7 and Nexus 4) were used in all our experiments to set up the WiFi connection for measurement. We let one smartphone (i.e., "server")

[2]WiFi radio noise floor is typically -95 dBm, so -80 dBm indicates an SNR of 15 dB.

[3]An actual implementation of ISM side-channel may re-use parts of WiFi PHY and/or MAC, but our emphasis is only to characterize the theoretical benefit of using the ISM band.

initiate a WiFi Hotspot and the other device (i.e., "client") can request to join this network. After the connection is complete, the channel strength can be measured from the client side.

We developed two Android apps, one for server and one for client. The two apps were developed on a Windows 64-bit platform: JDK 1.6.0_37, Eclipse Helios Service Release 2 as the development IDE and Android SDK 4.3 (API 18). The client app records the WiFi received signal strength indicator (RSSI) and SSID, along with the timestamp of each measurement, GPS location of the device.

2.2 Channel Measurement Results

We conducted measurement campaigns to measure the WiFi channel strength for both intra-vehicle and inter-vehicle environments. In our experiments, we collected 1000 samples for each measurement recording.

For the intra-vehicle experiment, one smartphone was placed at the front seat of a compact car, and the other smartphone was positioned at the back seat of the car with a separation of 1.5 meters. The resulting average RSSI is -34.5 dBm with a standard deviation of 5.5 dBm. Due to size limit of the vehicle we had for the experiment, we also conducted a high-scattering indoor experiment to mimic the intra-vehicle environment such as van or limousine. This campaign was conducted inside the engineering building at Rice University where a cluttered room was filled with chairs, desks, and people walking around. We placed the two smartphones at different distances, and measured the corresponding WiFi channel strength. Figure 4 illustrates the empirical WiFi link quality between smartphones in a high-scattering environment which mimics the intra-vehicle environment. Within 10 meters range test, the RSSI varies from -41 dBm to -63 dBm which corresponds to an SNR of 32 to 54 dB (assuming the WiFi noise floor is -95 dBm). The result shows that we can expect a reliable ISM side-channel to exist between smartphones in the same vehicle within 10 meters range.

Another measurement campaign was performed to characterize inter-vehicle environment. We conducted the experiment in a parking lot at Rice University. Two vehicles each of which has a smartphone inside were parked at different distance separation. In Figure 5, over the range up to 50 meters we tested, the average RSSI is always above -80 dBm which indicates an SNR of 15 dB. Thus we can expect a reliable side-channel to exist between inter-vehicle smartphone users within 50 meters range. We expect that as device-to-device communication gains more traction, the link quality and range may improve over time.

2.3 Analysis with Highway Traffic Data

We used the rush hour traffic counts from annual traffic data provided by California department of transportation [1]. During the rush hour, the physical traffic is very congested. More physical congestion will likely result in higher network congestion since more users will be served in the cell. It is also a more relevant use case of ISM side-channels since this is exactly when cellular systems may need to invoke more complicated methods to increase system capacity. From rush hour traffic counts at all count locations on 900 California highways including Interstate, California State Route, and United States Route, we first compute an approximate vehicle-to-vehicle (V2V) range which is defined

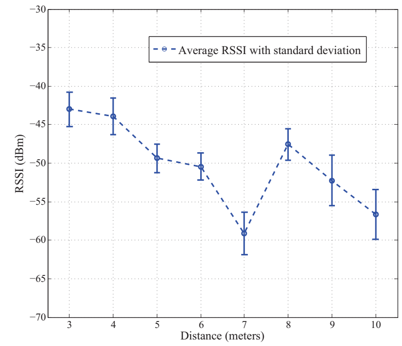

Figure 4: RSSI versus distance for high-scattering environment which mimics intra-vehicle environment.

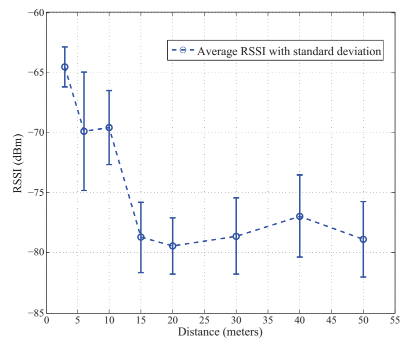

Figure 5: RSSI versus distance for inter-car environment.

as

$$\text{V2V range(meter)} = \frac{\text{Avg Rush Hour Speed(meters/hour)}}{\text{Rush Hour Traffic Counts(vehicles/hour)}}.^4$$

Figure 6 shows the histogram of V2V range. We see that 69% of the time, one can expect another vehicle within 50 meters range. Given that our previous experiments showed

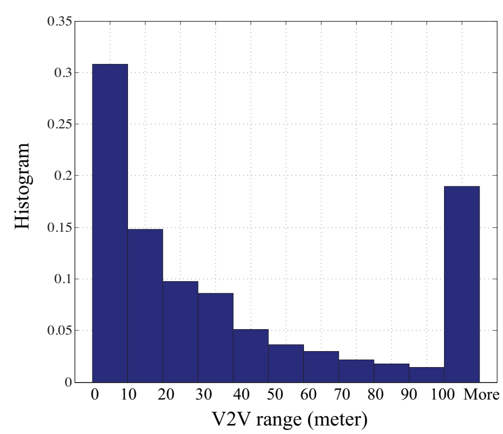

Figure 6: Estimate on the availability of ISM side-channels based on V2V range distribution.

[4] We used 40 miles/hour as an average highway rush hour speed.

that the inter-vehicle WiFi link exists for ranges less than 50 meters, and assuming at least one smartphone per vehicle, *we conclude that during rush hour, one can expect 69% of the time we will have at least one inter-vehicle ISM side-channel.* Of course, if there are multiple smartphones in one vehicle, then the probability of establishing an intra-vehicle ISM side-channel with reliable link quality is almost one, since most vehicles are less than 50 meters in length.

3. IMPACT ON CELLULAR CAPACITY OF FUTURE WIRELESS ARCHITECTURES

MU-MIMO and full-duplex communication are two promising techniques which can substantially improve the spectral efficiency over the traditional wireless system such as TDMA. However, as we will discuss in the following sections, the intra-cell interference originated in the new wireless systems can lead to substantial performance degradation. We will show the significant capacity gains with ISM side-channels for improved interference management. We assume a base station is equipped with M antennas, serving K downlink and L uplink users in the cell, and $M \geq K,\ L$.

3.1 Half-duplex MU-MIMO Downlink

3.1.1 Inter-beam Interference

One common approach used in MU-MIMO downlink is zero-forcing beamforming (ZFBF) [12]. The ZFBF system can achieve the full multiplexing gain (i.e., $\min\{M, K\} = K$) for MU-MIMO downlink. When the transmitter has perfect channel state information (CSIT), ZFBF can completely eliminate multi-user interference, which creates a parallel, non-interfering channel to each user.

However, in a practical MU-MIMO system, a base station with large number of antennas faces the challenge of acquiring large number of channel coefficients, which need to be estimated and fed back to the base station within a small fraction of the coherence time. The situation is further complicated by the fact that the channel coefficients will incur pilot contamination [8] if the pilots for channel estimation are sent at the same time as the pilots of neighboring base-stations. Thus the channel knowledge acquired by the base station is not perfect. The ZFBF system is extremely sensitive to the accuracy in CSIT. The imperfect CSIT not only leads to a decrease in the desired signal power but more importantly, makes it impossible to form a very sharp beam toward each user without causing interference to others. Therefore unavoidably there exists *inter-beam interference* among the users in a practical ZFBF system.

To capture the imperfection of CSIT, a finite rate feedback model was introduced in [7], in which each user quantizes its channel instantiation to a finite number of bits that are fed back to the transmitter at the beginning of each block in block fading channels. Then the base station computes the beam weight vector according to the quantized channel. Because of the quantization error, the inter-beam interference can not be completely eliminated. From [7], we can find out the upper bound to the rate of ZFBF system with a finite-rate feedback where the feedback quality is fixed at high signal-to-noise ratio (SNR):

$$R_{\text{FB}}(\mathsf{SNR}) \leq K\left(1+\frac{B+\log_2 e}{K-1}+\log_2 e+\log_2(K-2)\right), \quad (1)$$

where B is the number of feedback bits per user. From (1), we can see that the full multiplexing gain vanishes due to inter-beam interference if the feedback quality is fixed, namely, B does not scale with increasing SNR. Thus R_{FB} does not scale with respect to SNR.

3.1.2 Capacity Improvement

In this section, we first analytically show the capacity benefits of leveraging ISM side-channels to manage the inter-beam interference in ZFBF system. In a dense environment, via ISM side-channels, we can perform user-cooperation [10] among the mobile users. In the user-cooperation scheme, the base station does not acquire any CSIT, thus it will blindly transmit signals to the downlink users using only K antennas. Each user will first amplify-and-forward the received signal to other users via the ISM side-channels. Then each user can perform receive beamforming based on the its own channel knowledge and the transferred channel knowledge from other users to null out the interference. The partition of time slots of the user-cooperation scheme is shown in Figure 8 as compared with ZFBF with feedback.

At high SNR, the rate of user-cooperation via ISM side-channels [10] can be approximated as

$$R_{\text{ISM}}(\mathsf{SNR}) \approx K\log_2(\mathsf{SNR}). \quad (2)$$

Thus with ISM side-channels, the full multiplexing gain can be recovered even without CSIT, which significantly improves upon ZFBF with a fixed feedback quality. Also note that without CSIT, the multiplexing gain in the MU-MIMO downlink is only one [6].

Now we will verify our analysis with simulation results based on our measurements. The simulation parameters are listed in Table 1. We assume as the number of user density increases, the inter-user distance reduces. Figure 7 depicts the downlink cell capacity as a function of the downlink user density. We can see that the user-cooperation significantly improves upon ZFBF with finite feedback where the number of feedback bits per user is 10. As the density of the downlink users increases, the inter-beam interference due to finite feedback in ZFBF system become severe, thus limiting the cell capacity and number of users which can be served in the area. Also, the capacity of ZFBF even with perfect CSIT will start to decrease as the number of downlink users become larger. This is because some portion of the total transmit power is dispersed to create more nulls per user, which leads to a decrease in the desired signal power.

We note that the ZFBF with perfect CSIT will perform better than user-cooperation due to the fact that ZFBF with perfect CSIT uses all base station antennas to provide higher power gain, while for user-cooperation, since we eliminate the acquisition of CSIT, we only use a subset of the antennas for downlink transmission. However, when we have asymmetric traffic demand (i.e., both uplink and downlink traffic), we can exploit the remaining antennas to support uplink streams which allows full-duplex operation, as described in the next section.

3.2 MU-MIMO Full-duplex with Half-duplex Clients

In this section, we will demonstrate how ISM side-channels will enable a flexible wireless system design, a new wireless architecture of MU-MIMO full-duplex which would not be feasible due to the intra-cell interference (i.e., both inter-

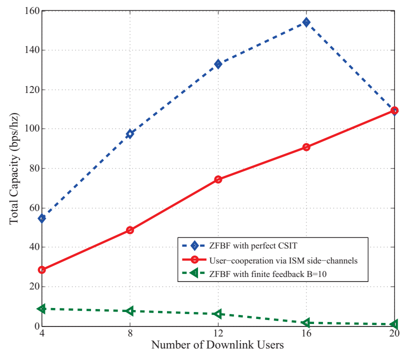

Figure 7: Cell capacity of downlink traffic as a function of the downlink user density.

beam interference and uplink-downlink interference). Then we will show the significant capacity improvement of our MU-MIMO full-duplex system via ISM side-channels.

3.2.1 Uplink-downlink Interference

With ISM side-channels, only K out of M antennas at the base station are needed to achieve the full multiplexing gain in MU-MIMO downlink. When we have asymmetric traffic demand of both up- and downlink flows , we can employ the remaining $M-K$ antennas to enable full-duplex operation at the base station [5] by adopting different kinds of spatial isolation techniques such as polarization, directionality and absorption. With full-duplex capability at the base station, ideally up to $M-K$ uplink streams can also be supported simultaneously in addition to the K downlink streams using receive beamforimg techniques. However, in a dense environment where all users are within the communication ranges of each other, it is inevitable that the uplink streams will interfere with all downlink streams since both the up- and downlink streams are in the same resource block as shown in Figure 2. Not only we can not harvest the benefits of having full-duplex operation, but also we will harm the downlink users. The gain of full-duplex will vanish because of such *uplink-downlink interference* [3] especially in a clustered environment.

In [2], we show that one simple scheme called decode-and-cancel via ISM side-channels can completely recover the full-duplex multiplexing gain. In decode-and-cancel, the uplink user will encode its main-channel (cellular band) message using an independent codebook and send the coded messages to the downlink user through the ISM side-channel. The downlink user then will decode the uplink message from the side-channel, form the main-channel interfering signal locally, and subtract out the interference from the main-channel. The decode-and-cancel scheme involves only single-user decoders, and allows the uplink user to encode the message using different modulation and coding schemes which can be adapted to the ISM side-channel condition.

3.2.2 Channelization of ISM Side-channels

In this section, we will illustrate how cellular providers can provide a more flexible and structured way for intra-cell interference management via ISM side-channels; this is one of the main reasons to let cellular providers handle the use of ISM bands without user intervention. First, the base station will orthogonalize the downlink and uplink transmission of pilots for channel estimation as shown in Figure 8. During the training period of uplink channels, the downlink users can overhear the uplink pilots to estimate the interference channel between the up- and downlink users. Then the base station will start the data transmission for downlink and reception for uplink simultaneously. Since usually the ISM band has much larger bandwidth than that of the licensed band, we can divide the whole bandwidth of ISM band into two parts, one (BW_1) is for downlink user-cooperation to resolve inter-beam interference. The other part (BW_2) is used to manage the uplink-downlink interference.

Area	50×50 square meters
Base station antennas	$M = 20$
Maximum number of users	$K + L = 20$
Uplink and Downlink SNR	35 dB
ISM Side-channel RSSI	Refer to our measurement in Figure 5
Main-channel	QPSK uncoded system under Rayleigh fading

Table 1: Simulation parameters

In each sub-band of ISM band, we will partition the time slots for the corresponding participating users. As illustrated in Figure 8, the kth downlink user amplifies-and-forwards its received signal to other participating downlink users in time-slot T_{D_k} in ISM band BW_1. The ith uplink user will use decode-and-cancel scheme to broadcast the coded copy of its message in time-slot T_{U_i} in ISM band BW_2. The downlink receivers will then decode the uplink message in ISM band BW_2, and subtract out the interference from the main-channel using the channel knowledge of the interference channel. Finally, downlink users can perform receive beamforming with the help of user-cooperation.

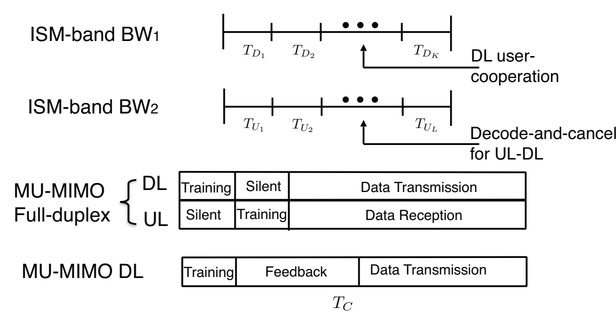

Figure 8: Comparison of channel training - data structure between MU-MIMO full-duplex via ISM side-channel and half-duplex MU-MIMO downlink in a given coherence time T_c. The time-slot partition of the ISM band for downlink user-cooperation and uplink-downlink decode-and-cancel is also given.

In comparison, in the MU-MIMO downlink, the base station first sends pilots for channel estimation, and then each user will feedback the estimates to the base station which requires $O(M \times K)$ time slots since there are K users and M antennas at the base station. We can see that the overhead of obtaining CSIT is prohibitive especially in large antennas regime, which considerably limits the rate of data transmission given the coherence time T_c.

3.2.3 Capacity Improvement

Based on our analytical calculation [3], we can achieve a maximum multiplexing gain of M with ISM side-channels for improved intra-cell interference management,[5] while the multiplexing gain of MU-MIMO downlink system is K, and for TDMA system, the multiplexing gain is only one. Hence theoretically our system with ISM side-channels can at most improve the capacity of MU-MIMO downlink by $\frac{M}{K}$-fold and traditional TDMA by M-fold.

We now illustrate the capacity gains by simulation; the details are listed in Table 1. Figure 9 compares the cell capacity of four systems: 1) TDMA where all the antennas are used to serve one flow at a time; 2) half-duplex ZFBF downlink with perfect CSIT where all the antennas are used for downlink transmission; 3) full-duplex ZFBF with perfect CSIT where a subset of antennas are used for downlink and the rest are used for uplink; 4) MU-MIMO full-duplex via ISM side-channels where no CSIT is required for the downlink and the uplink streams are decoded via receive ZFBF. We have a fixed up- and downlink user density. We find out our MU-MIMO full-duplex system via ISM side-channels achieves the highest capacity among the four. The capacity gain over ZFBF with perfect CSIT half-duplex downlink can be as high as 6× in this particular case and is proportional to $\frac{M}{K}$-fold which agrees with our theoretical analysis. The gain over TDMA is as high as 12×. Further, we can see that without ISM side-channels, even with perfect CSIT the full-duplex gain vanishes as the number of downlink users increases. In contrast, leveraging the ISM side-channels of mobile users can substantially alleviate the uplink-downlink interference thus recovering the 2× full-duplex gain.

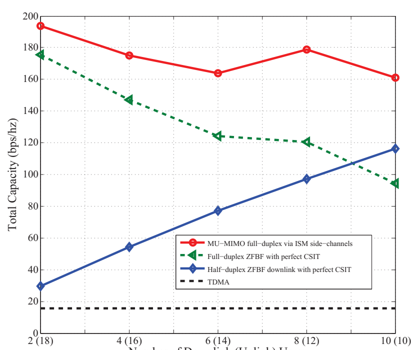

Figure 9: Cell capacity of asymmetric traffic with a fixed up- and downlink user density.

We also present the capacity benefit of ISM side-channels with respect to availability range distribution of ISM side-channels. In an area of 50 meters length, we can compute the conditional probability distribution based on our empirical results in Section 2.3.[6] In Figure 10, we show the expected capacity, i.e., $\mathbb{E}_d\big[\text{Capacity}(d)\big]$, where the capacity is a function of the inter-user distance d. The expectation is taken over the conditional probability distribution. We can see that the expected capacity of our ISM side-channels system performs the best among the four, and the gains scale with increasing SNR.

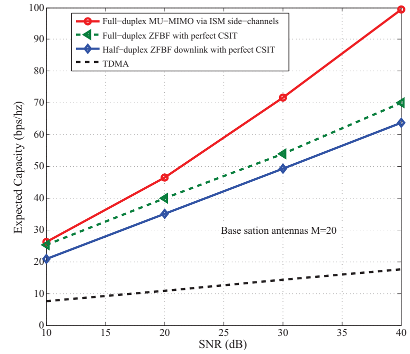

Figure 10: Expected capacity of asymmetric traffic as a function of SNR.

4. CONCLUSION

The idea of leveraging ISM side-channels for improved interference management promises to improve the network capacity many-fold. However, there still remains critical challenges of protocol design and mobile energy efficiency that need to be addressed in the future work.

Acknowledgment

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[5]Under the condition that the ISM side-channel strength is above certain SNR dependent threshold.

[6]The conditional probability for a given distance range(x,y] can be computed as $\text{Prob}\big((x,y]\ |\text{distance}\leq 50\big)$.