

Rethinking the Role of Interference in Wireless Networks

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Abstract

This article re-examines the fundamental notion of interference in wireless networks by contrasting traditional approaches to new concepts that handle interference in a creative way. Specifically, we discuss the fundamental limits of the interference channel and present the interference alignment technique and its extension of signal alignment techniques. Contrary to this traditional view, which treats interference as a detrimental phenomenon, we introduce three concepts that handle interference as a useful resource. The first concept exploits interference at the modulation level and leads to simple multiuser downlink precoding that provides significant energy savings. The second concept uses radio frequency radiation for energy harvesting and handles interference as a source of green energy. The last concept refers to a secrecy environment and uses interference as an efficient means to jam potential eavesdroppers. These three techniques bring a new vision about interference in wireless networks and motivate a plethora of potential new applications and services.

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I. INTRODUCTION

Resources (e.g. time, frequency, code) have to be shared by multiple users in wireless networks. Therefore, interference has long been considered as a deleterious factor that limits the system capacity. In conventional communications systems, the design objective is to allow users to share a medium with minimum or no interference. Thus, great efforts are made to avoid, mitigate and cancel interference. For instance, to support multiple users, orthogonal access methods in time, frequency, code as well as spatial domains have been used in different generations of cellular systems. In future-generation heterogeneous cellular networks, due to the increasing number of uncoordinated low-power nodes in such as femtocells to improve the coverage and capacity, interferences need to be mitigated in multiple domains, rendering their management a challenge.

Interference mitigation/avoidance techniques provide convenient mechanisms to allow multiple users to share the wireless medium. However, they lead to inefficient use of wireless resources. One may ask whether to cancel or mitigate interference is always the optimal way of utilizing wireless resources. Indeed, there has been growing interest in exploiting interference to improve the achievable rate, the reliability and the security of wireless systems. Recently, new views on interference have resulted in advanced interference-aware techniques, which, instead of mitigating interference, explore the potential of using interference. We present two examples from the literature to illustrate the ideas.

In his early work of dirty paper coding [1], Costa proved the striking result that interference known at the transmitter but not at the receiver does not affect the capacity of the Gaussian channel. The optimal strategy to achieve this interference-free capacity is to code along interference, while cancelling interference is strictly sub-optimal. Another example is coordinated multipoint or multi-cell coordination, where base stations (BSs) cooperate to serve their own and out-of-cell users. In the downlink, the cooperating BSs work together to jointly optimize the transmitter strategies such as power, time and beamforming design to control the inter-cell interference. Cell-edge users who suffer most from the inter-cell interference now benefit most from this coordination. In the uplink, jointly decoding is performed in BSs, so signals from users in other cells are no longer treated as interference, but as useful signals.

The purpose of this article is to re-examine the notion of interference in communications networks and introduce a new paradigm that considers interference as a useful resource. We first give an overview from the information theoretic standpoint as a justification for rethinking the role of interference in wireless networks. We then introduce interference alignment and signal alignment as effective means to handle interference and increase the achievable rates. Departing from this traditional view, we present three novel

techniques of interference exploitation that aim to improve the performance of wireless networks. The first technique is a data-aided precoding scheme in the multiuser downlink that judiciously makes use of the interference among users as a source of useful signal energy. In the second technique, we consider simultaneous information and energy transfer; in such a system, while interference links are harmful for information decoding, they are useful for energy harvesting. Thus, a favorable tradeoff is demonstrated. The third technique leverages interference in physical layer secrecy as an effective way to degrade the channel of the eavesdropper and increase the system's secrecy rate.

II. INTERFERENCE FROM THE INFORMATION THEORETIC STANDPOINT

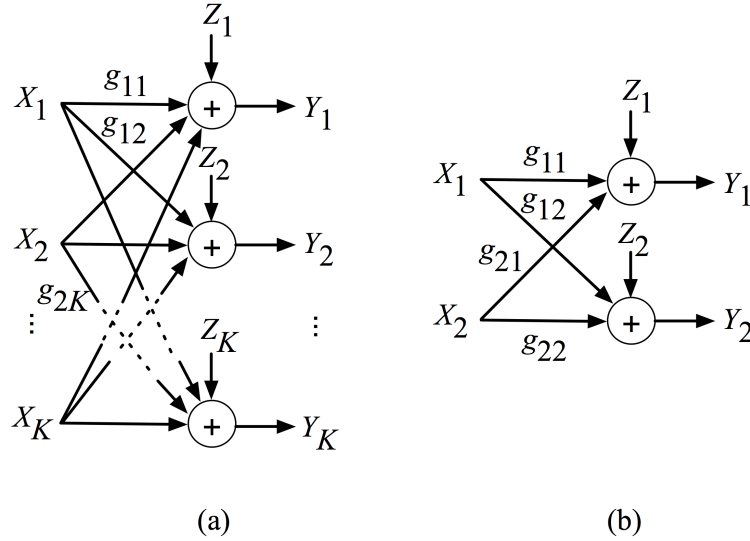


Fig. 1: (a) The K -user Gaussian Interference Channel (G-IC) (b) The 2-user G-IC.

We first present an overview of results on interference from information theory. The Interference Channel (IC) models simultaneous transmission by non-cooperating transmitters and receivers. The messages of each link are encoded only by the corresponding transmitter, and the receiver does not have access to the signals of other receivers. Figure 1(a) depicts the K -user Gaussian Interference Channel (G-IC). Each of K transmitters wants to send a message to the corresponding receiver. Receiver k bases its decision on signal Y_k , which contains not only the (scaled) useful signal X_k , but also interference and Gaussian noise.

Despite its apparent simplicity, to this date it is not known what the optimal way of transmitting over the G-IC is, not even for the 2-user G-IC shown in Fig. 1(b). Nevertheless, significant progress has

been made recently, and results from information theory have started influencing the design of wireless networks. The optimal decoding strategy depends on the power of interference compared to the direct links. Interference should be treated as noise when it is very weak. The exact conditions for the 2-user G-IC to be in the *very weak* regime can be found in [2]. In information theoretic terms, the messages of both transmitters are *private*, since they are only decoded at the intended receiver. On the other hand, when the power of the interfering signal exceeds the power of the signal of interest (*strong* interference), the optimal strategy is to also decode interference at the receivers. In this case, both messages are *public*. If the power of the interference exceeds an even higher threshold the G-IC is in the *very strong* interference regime and the rate that can be achieved by each link is the same as if the interferer did not exist, *i.e.*, interference does not impact the achievable rates. Nevertheless, the receiver does need to decode interference in addition to the signal of interest. Clearly, there are costs associated with interference-aware decoding. The receivers are more complex, synchronization is essential, and each receiver needs to estimate not only its own channel, but also the cross-channel coefficients.

The most challenging situation arises when the power of the interference is of the order of the power of the signal of interest. To this date it is not known what the best way to transmit and decode is. A strategy that combines public and private messages (the so-called Han & Kobayashi scheme [2]) achieves higher rates compared to treating interference as noise or avoiding it via orthogonal transmission, or attempting to decode all messages at each receiver. Moreover, it has been shown that as the signal-to-noise ratio (SNR) grows to infinity, a simplified Han & Kobayashi scheme can attain the capacity region within $1/2$ bit [2]. In addition to providing evidence that strategies based on the Han & Kobayashi scheme may be the best for the 2-user G-IC, this result may prove useful in future wireless networks with small cell size that will operate at high SNRs and will therefore be limited by interference rather than by noise.

Devising good strategies for the K -user G-IC seems to be even more challenging, and the Han & Kobayashi scheme does not appear to extend to the K -user G-IC in a straightforward manner. A promising direction towards finding good strategies for the K -user G-IC appears to be dealing with the combined interference by all $K - 1$ users at each receiver instead of decoding separately the interference by each user. Furthermore, a deterministic approximation framework has been developed for the G-IC, which enables the construction of structured codes [2]. By employing structured lattice codes, which are also used in other scenarios, such as multi-way relay channels, it is possible to attain the capacity region of the G-IC within a constant gap [3]. Very recently, there has been an interesting finding that connects topological interference management and index coding [5]. This connection can be leveraged to calculate rate regions that are within a constant gap from capacity and to develop transmission schemes over

wireless networks. The existing index coding solutions are then translated to interference management solutions via a family of elegant achievability schemes of interference alignment (IA) that has generated significant interest, which is discussed in more detail in Section III.

System designs that operate based on the best known achievability schemes of information theory being the ultimate goal, in the meantime improvements in performance can also be attained by incorporating interference-aware schemes in current systems. In [6] it is shown that when the transmitters use discrete constellations and interference-aware detectors are employed at the receivers the achievable rates over the fading G-IC are limited by the SNR rather than by the signal-to-interference-plus-noise ratio (SINR).

III. INTERFERENCE AND SIGNAL ALIGNMENT

Prior to the invention of IA [4], interference avoidance has been achieved by relying on the use of orthogonal frequency or time channels. And when interference is inevitable, conventional approaches are to adopt advanced decoding/detecting algorithms by treating interference as noise.

The success of IA lies in the fact that it efficiently exploits the rich degrees of freedom available from the time/frequency/spatial domains. By a careful coordination among the transmitters, the use of IA can ensure that all the interference is aligned together to occupy one half of the signal space at each receiver, leaving the other half available to the desired signal. As a result, the per-user rate achieved by IA for the interference channel with K pairs of single-antenna transceivers is $C(SNR) = \frac{1}{2} \log(SNR) + o(\log(SNR))$. This result is surprising since a traditional view is that such a K -user scenario is interference limited and hence the per-user rate is diminishing by increasing the number of users. As a result, the use of IA ensures that the spectral efficiency of wireless communications can be improved significantly since more users sharing the same bandwidth yields a larger system throughput.

In addition to interference channel, the concept of IA has also been applied to other communication scenarios, including multiple access channel, broadcast channel, one/two-way relaying channel as well as physical layer security. In practice, the implementation of IA is not trivial since the global channel state information at each transmitter (CSIT) is required, which is challenging particularly for the case with fast time varying channels. Two types of approaches to realize IA in practice have been proposed.

One is to apply advanced feedback techniques and existing results have demonstrated that the number of feedback bits needs to be proportional to the SNR in order to achieve nearly optimal performance [9]. The other is to exploit the coherent structure of channels and apply manipulations analog to space time coding at the transmitters. As a result, the concept of IA can be implemented even when the channel information is not available to the transmitters.

The concept of signal alignment can be viewed as an extension of IA in the context of bi-directional communications [10] and [11]. For example, consider a multi-pair two-way relaying communication scenario as shown in Fig. 2, where M pairs of source nodes exchange information with their partners via the relay. Each source node is equipped with N antennas, and the relay has M antennas. As can be seen from Fig. 2, the relay observes $2M$ incoming signal streams, and needs to have at least $2M$ antennas in order to separate these signals. The use of signal alignment is to effectively suppress intra-pair interference and reduce the requirement to the number of antennas at the relay. Particularly, by carefully designing the precoding vectors at the sources, the intra-pair interference is aligned at the relay, which means that the original $2M$ signal streams are merged into M streams. As a result, a relay with only M antennas can accommodate $2M$ incoming signals, which is particularly important for practical scenarios where nodes are equipped with a limited number of antennas. At the user end, each receiver can first subtract its own information, the so-called self-interference, and then detect the information from its partner, a way analogous to network coding.

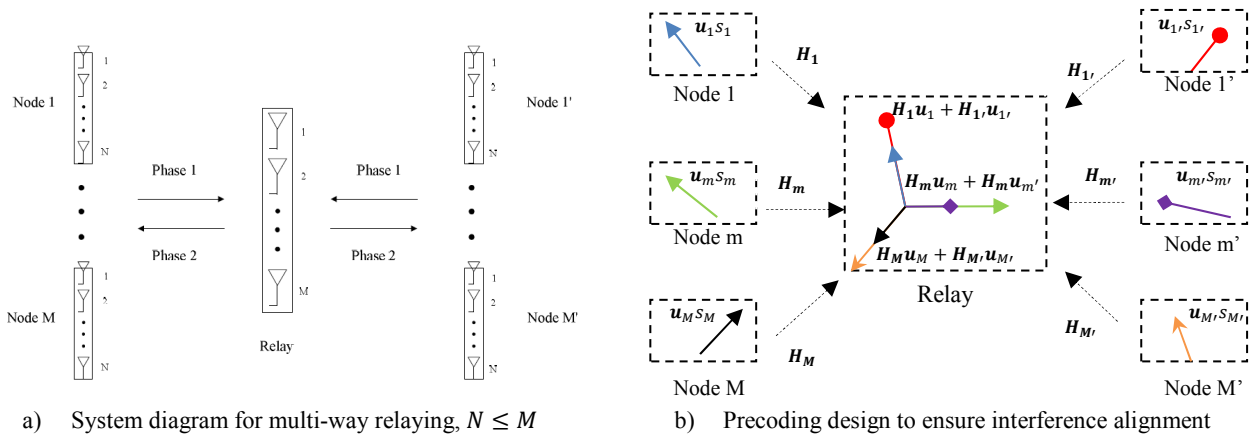


Fig. 2: Illustration of the concept of signal alignment.

IV. DATA-AWARE INTERFERENCE EXPLOITATION FOR MULTIUSER TRANSMISSION

The *a priori* knowledge of interference is readily available at downlink transmission, where CSIT combined with the knowledge of all data symbols intended for transmission can be used to explicitly predict the resulting interference between the symbols. Despite the insights in [1], the majority of existing precoding implementations attempt to eliminate, cancel or pre-subtract interference. Only recently however, has there been a rising interest in making use of the interference power to enhance the useful

signal [7], [8]. Indeed, it has been shown that interference can contribute constructively to the detection of the useful signal and this phenomenon can be utilized in the CSIT-assisted downlink transmission and other known-interference scenarios to improve performance without raising the transmit power.

To clarify the above fundamental concept, a trivial example of two users is shown in Fig. 3(a), where we define the desired symbol as x_1 and the interfering symbol as x_2 . Without loss of generality we assume that these belong to a Binary Phase Shift Keying (BPSK) constellation and that $x_1 = 1, x_2 = -1$. For illustration purposes, we assume a lossless channel from the intended transmitter to the receiver and an interfering channel represented by the coefficient ρ . Ignoring noise, the received signal is

$$y_1 = x_1 + x_2 \cdot \rho, \quad (1)$$

where $x_2 \cdot \rho$ is the interference. Note that this model also corresponds to a multi-antenna transmission with matched filtering where the correlation between the two channels is ρ . In Fig. 3(b) two distinct cases are shown, depicting the transmitted (\times) and received (\circ) symbols for user 1 on the BPSK constellation. In case i) with $\rho = 0.5$ it can be seen from (1) that $y_1 = 0.5$. The destructive interference from user 2 has caused the received symbol of user 1 to move towards the decision threshold (imaginary axis). The received power of user 1 has been reduced and its detection is prone to low-power noise. In case ii) however, for $\rho = -0.5$ (1) yields $y_1 = 1.5$, and hence the interference is constructive. The power received has been augmented due to the interference from user 2 and now its detection is tolerant to higher noise power (n_{constr} compared to n_{orth}). It should be stressed that in both cases the transmit power for each user is equal to one. Note that, while the above example refers to a two-user transmission scenario for illustration purposes, the fundamental concept can be extended to more users, multipath transmission, inter-cell interference and other generic interference-limited systems.

Clearly, there are critical gains to be drawn from the exploitation of constructive interference in interference-limited transmission. As a first step, analytical constellation-dependent characterization criteria for systematically classifying interference to constructive and destructive have been derived in [7], [8] and references therein for PSK modulation. Early work carried out on a simple linear precoding technique has reported multi-fold increase in received SNR for fixed transmit power compared to zero-forcing (ZF) beamforming [7]. This can be nontrivially translated to multi-fold savings in transmit power for a fixed received SNR. A representative result is shown in Fig. 4(a) where the required SNR per transmit antenna in a cellular downlink for an uncoded symbol error rate (SER) of 10^{-2} is shown for increasing numbers of single-antenna users. The results compare the widely known ZF precoding with the interference exploitation precoding of [7] for QPSK and 8PSK modulation. Significant SNR gains of

up to 10dB (a 10-fold transmit power reduction) can be observed between the two techniques, by simply exploiting the existing constructive interference.

Further work has investigated the application of this concept on advanced nonlinear precoding, yielding further significant gains in the transmit power. More recent work has extended this concept to inter-cell interference exploitation in multi-cellular transmission scenarios [8]. The important feature in all the above techniques is that the performance benefits are drawn not by increasing the transmit power of the useful signal, but rather by reusing interference power that already exists in the communication system; a source of green signal power that with conventional interference cancellation techniques is left unexploited.

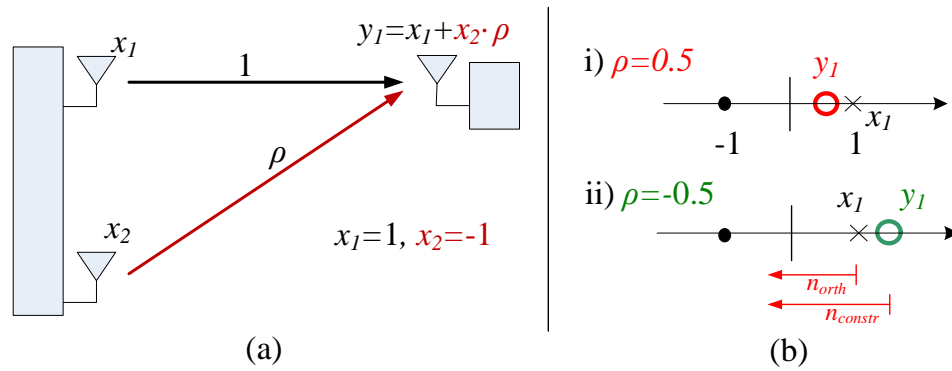


Fig. 3: The concept of constructive interference — a two-user example.

V. WIRELESS INFORMATION AND ENERGY TRANSFER

Energy harvesting (EH) communication systems that can scavenge energy from a variety of natural sources (solar, wind, etc.) for sustainable network operation have attracted significant interest. The main limitation of conventional EH sources is that they are weather-dependent and thus not always available. A promising harvesting technology that could overcome this bottleneck is radio frequency (RF) energy transfer where the ambient RF radiation is captured by the receiver antennas and converted into a direct current voltage through appropriate circuits (rectennas). The concept of RF-EH is not new; over 100 years ago, Nicola Tesla proved and experimentally demonstrated the capability of transferring energy wirelessly. The integration of RF-EH technology into communications networks opens new challenges in the analysis and design of transmission schemes and protocols. Multi-user interference, which is the main degradation factor in conventional networks, can be viewed as useful energy signals that could be exploited for harvesting purposes. Although from an information theoretic standpoint the same signal

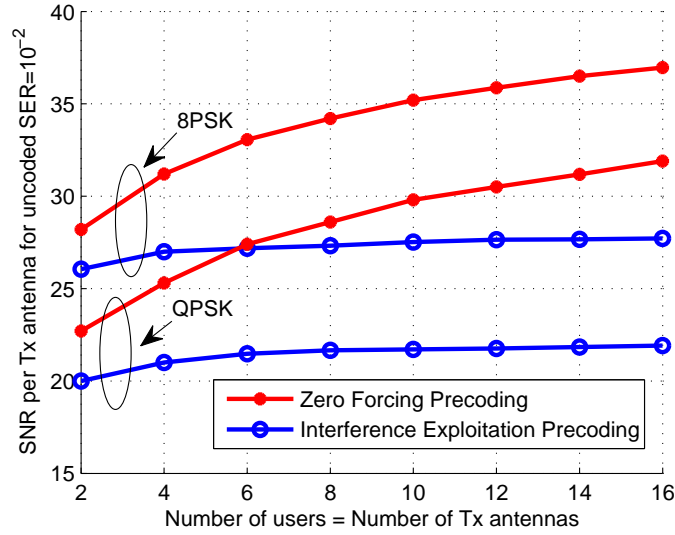


Fig. 4: Required SNR per transmit antenna for an uncoded SER of 10^{-2} with increasing numbers of users and transmit antennas.

can be used for both decoding and EH, due to practical hardware constraints, simultaneous energy and information transmission is not possible with existing rectenna technology. Two practical receiver approaches for simultaneous wireless power and information transfer are a) “time switching” (TS), where the receiver switches between decoding information and harvesting energy and b) “power splitting” (PS), where the receiver splits the received signal in two parts for decoding information and harvesting energy, respectively [12].

An interesting implication of the PS technique is that in multiuser networks harvested energy at a particular receiver can emanate either from sources that intentionally transmit towards that direction or from other sources whose signal is traditionally perceived by that receiver as interference. Nonetheless, in this case the contribution of useful and interfering signals towards the satisfaction of any RF-EH requirements is equally important. This implication changes completely the design philosophy of such networks, as interference becomes useful.

This concept was demonstrated for the multiple-input single-output (MISO) interference channel where K transmitters, each one with K antennas, communicate with K single-antenna receivers [13]; each receiver is characterized by both quality-of-service (QoS) and RF-EH constraints, while PS is used for simultaneous information/energy transfer. The QoS constraint requires the SINR to be higher than a given threshold, while the RF-EH constraint requires the power input to the RF-EH circuitry to be above

a threshold. In this framework, an interesting non-convex optimization problem arises in selecting the beamforming weights and the power of the transmitters as well as the power splitting ratios at the receivers so as to minimize the total transmit power. The problem can be solved optimally using semidefinite programming, while traditional beamformers can be employed to obtain suboptimal but low-complexity solutions. An interesting conclusion, is that for ZF beamforming there always exists a unique, optimal, closed-form power allocation.

The benefit of exploiting interference in the context of RF-EH is illustrated in Fig. 5, which depicts the transmit power ratio between ZF and optimal beamforming for varying SINR and RF-EH thresholds ($K = 8$). The figure indicates that by exploiting interference the transmit power can be significantly reduced, especially for low SINR. The reason is that for low SINR there is room to increase interference which is beneficial for RF-EH. In contrast, high SINR thresholds requires almost full cancellation of interference; hence, the solutions obtained from ZF are almost optimal. The benefits of interference exploitation can also be seen with respect to the RF-EH constraints: when the RF-EH threshold increases, the ZF/optimal power ratio increases because the optimal scheme manages interference better. However, the effect of the SINR constraint on the transmit power ratio is more significant compared to the RF-EH constraint.

VI. INTERFERENCE-AIDED SECRECY RATE IMPROVEMENT

Due to the growing wireless applications, confidentiality and secret transmission has become an increasingly important issue. Recently, securing wireless communications at the physical (PHY) layer has been studied as a complimentary measure to upper layer cryptographic techniques. In the presence of eavesdroppers who passively overhear the communication, intentional interference plays a key role to improve the secrecy rate. This is understandable since interference will affect both systems, however, if properly designed, it can be an advantage for the legitimate system. This is indeed true as it has been shown in [14] that, the exploration of aggregated interference together with location and channel quality information, can significant improve network secrecy. In the following, we review several approaches that utilize interference to confuse the eavesdropper in a simple point-to-point network.

Consider a basic 3-node system which consists of a source S , a destination D and an eavesdropper E . When S has multiple antennas, it can transmit information bearing signal to D in the range space of the channel to D and also generate artificial noise (AN) to E in its null space simultaneously. In this way, even without knowledge of the instantaneous CSI of the eavesdropper, the generated AN does not interfere with the legitimate receiver D and only affects the eavesdropper node E . The same principle applies if

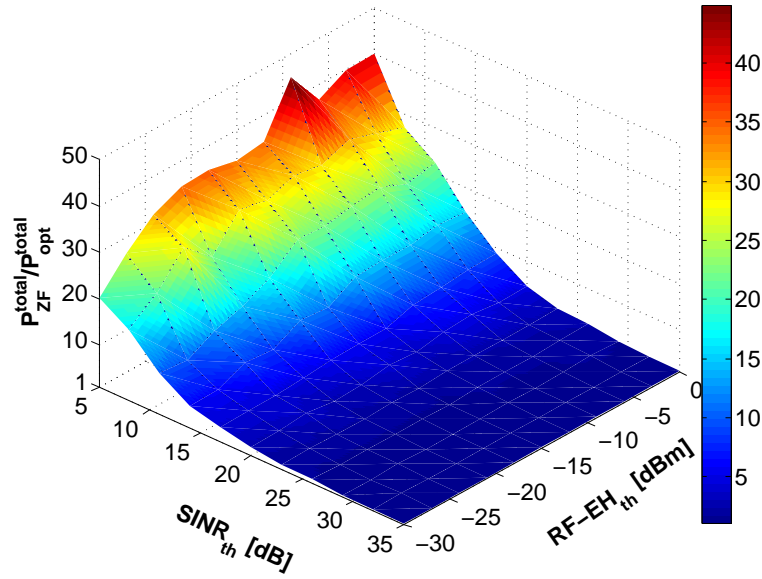


Fig. 5: Transmitted power benefit from optimal exploitation of interference compared to ZF beamforming to achieve SINR and RF-EH constraints in MISO interference channel.

there are trusted helper relays who could form distributed beamforming to transmit cooperative jamming signals to E.

When neither multiple antennas at S nor trusted helpers are available, the system must rely on itself to achieve secure communication. To this end, a self-protection scheme has been proposed that adopts

full-duplex (FD) operation at D to improve the secrecy rate [15], as shown in Fig. 6. More specifically, an FD receiver is introduced that simultaneously receives its data while transmitting a jamming signal to confuse E. The proposed approach uses intentional interference at D to confuse the eavesdroppers and does not require external helpers or data retransmission. Due to the FD operation, the receiver experiences a loop interference (LI) introduced by the transmitted jamming signal. If D has multiple transmit or receive antennas, it can employ joint transmit and receive beamforming for simultaneous signal detection, suppression and intentional jamming.

In Fig. 6, the achievable secrecy rate is evaluated against transmit SNR. We simulate two cases: i) single transmit/receive-antenna receiver and eavesdropper and ii) the receiver has two transmit and two receive antennas while the eavesdropper has four antennas for fairness. For the single-antenna case, it is seen that the FD scheme outperforms the HD operation for transmit SNR greater than 10 dB, and double secrecy rate is achieved in the high SNR region. The performance of the HD scheme saturates when the transmit SNR is higher than 20 dB. When the receiver has multiple antennas and the eavesdropper adopts a simple MRC receiver, the secrecy rate strictly increases with the transmit SNR and does not saturate at high SNR as the half-duplex (HD) case. When the eavesdropper is aware of the FD operation at D and adopts the minimum-mean-square-error (MMSE) receiver to mitigate the jamming signals from D, the achievable secrecy rate saturates at a high SNR of 40 dB but is still significantly higher than the case with HD receiver. This reveals the great potential of using interference at the receiver side to provide self-protection against eavesdropping.

VII. CONCLUSIONS

In this article, we have introduced radical views on interference in wireless networks. Traditional interference mitigation techniques are no longer optimal, and innovative ways of utilizing interference are emerging. As more aggressive resource sharing and tighter cooperation are foreseen in future wireless networks, interference management will continue to be a growing challenge. Accordingly, it is essential to further these new perspectives on interference for more efficient radio resource utilization in advanced wireless concepts such as large-scale antenna arrays (massive MIMO), multicell cooperation, cognitive radio and heterogeneous networks. Indeed, the employment of massive MIMO in future networks, allows the mitigation of interference using simple linear operations. This way, interference could be “available” in the network for other purposes without affecting its performance; this scenario motivates new services and applications. In future cloud radio access networks, baseband processing will be shifted from BSs to the central baseband unit pool to jointly process data to and from multicells, and this gives great

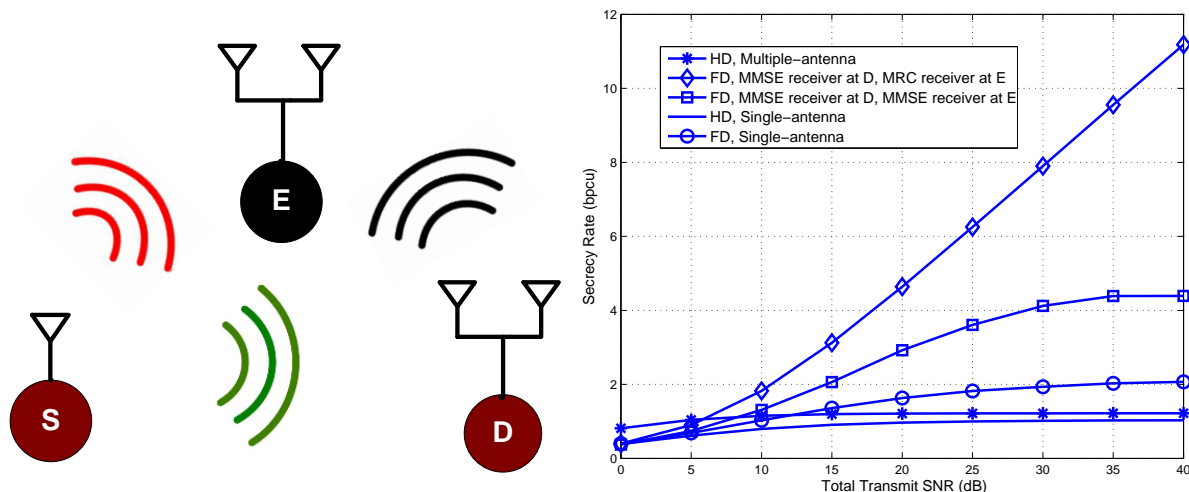


Fig. 6: Left: FD operation at the receiver that creates self-interference to improve the secrecy rate. Right: achievable secrecy rate in bits per channel use (bpcu) vs transmit SNR in dB.

opportunities to fully utilize interference. In cognitive radio, the interference from the secondary user to the primary user can facilitate RF energy transfer and be tuned into useful signals if the primary data is known at the secondary user. Regarding security in heterogeneous networks, a promising direction is to study how network interference can be engineered to best benefit wireless network secrecy.

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