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Communications over Two-way Waveform Channels in Wireless Networks

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Abstract

Two-way channels appear in wireless cellular networks as the duplexing between the base station and the mobile users and in wireless local area networks as the peer-to-peer communications. In this paper, we examine the two-way channel capacity and find that the capacity of two-way discrete channels and waveform channels without the knowledge of self-interference is the same as that of one-way channels. With the knowledge of self-interference, the capacity of a waveform two-way channel is twice that of a one-way channel.

Keywords: two-way channels, information theory, wireless communications.

Topic areas: Communications and Wireless Systems, Computer Networks and Communications, Signal Processing and Filter Design.

I. Introduction

Two-way channels [1,2], i.e., one channel with two-way communications, composed of two nodes, each with a transmitter and a receiver, communicating with each other, have found wide applications with the development of wireless networks. In wireless cellular networks, two-way channels appear as the duplexing [3] between the base station and the mobile users, i.e., the up-link (reverse) and the down-link (forward) channels. In wireless local area networks [4], two-way channels can describe the peer-to-peer communications, i.e., the communication between nodes directly without the aid of the base station. Since the frequency bandwidth currently usable is limited by technology, and the power consumption has to be low to achieve personal communication services, how to achieve two-way communications efficiently is an issue that needs to be investigated.

Two-way channel was introduced by Shannon in [1]. As Verdu mentioned, the work [1] also "marks the foundation of the discipline of multiuser information theory" [5]. That is, "the transmission capabilities of the two-way channels are not described by a single number (capacity) as the conventional one-way channel but by a two-dimensional 'capacity region' that specifies the set of achievable rate pairs". In [1], Shannon "gave a limiting expression for the capacity region of the discrete memoryless two-way channel. Unfortunately, it is not yet known how to explicitly evaluate that expression even in 'toy' examples. Of more immediate use were the inner and outer bounds found in [1], and later improved in [6]-[9]." [5]

Recently, Cover and Thomas [2] proposed that the two-way channels can be decomposed into two independent channels, each achieving the capacity of a one-way channel if a node can subtract out the codewords sent by itself when receiving the information from the other node. In other words, it is possible for the two nodes to send information simultaneously at a rate equal to the capacity of a one-way channel. In currently used wireless systems, two-way channels are realized by frequency-division duplexing, as in GSM, IS-54, and IS-95 [3], or time-division duplexing, as in PACS-UB, PHS, [3] and IEEE 802.11 [4]. In these two forms of two-way communications, however, the sum of the information rates in both directions often only achieves the same level of one-way communication. That is, the channel capacity is time- or frequency-shared by the two directions of communications. In practice, the achievable rate may be even lower due to the collisions of packets as in wireless local area networks [4]. The idea proposed by Cover and Thomas [2] has not been not carried out because how to "subtract" in practice is quite unclear, and it might be quite difficult for the discrete two-way channels [1] to achieve such capacity. For example, if we use BFSK (binary frequency shift keying) [10], the codewords we are able to examine at a node are the codewords sent by its transmitter, and it is quite difficult to subtract out its own codewords to obtain the codewords sent by the other node.

Therefore, we will present some possible solutions based on the examination of the "waveform" two-way channels in this paper. By doing so, doubling in the user capacity for wireless cellular systems and finding solution to self-interference (collision) problem to enhance capacity of wireless local area networks are quite possible.

Related work is as follows. An excellent review of communication networks and information theory is in [11]. In [11], possible directions for future research are also provided. In [12], Schulman investigated coding for interactive communication. He investigated how to solve a computation problem by the processors linked by a noisy communication link. In [13], van der Meulen provides an overview of the advances on the interference channel. More issues in signal processing perspectives for wireless communications can be found in [14,15].

The rest of this paper is organized as follows. Section II provides the preliminaries. Section III analyzes the channel capacity and presents the suppression of self-interference. Section IV provides the discussions and the conclusions.

II. Preliminaries

Some concepts needed for the analysis of channel capacity are reviewed here. For more details, please refer to [2].

Entropy

Definition:

The *entropy* $H(X)$ of a discrete random variable X with probability mass function $p(x) = \Pr\{X = x\}$, $x \in \chi$ is defined as

$$H(X) = -\sum_{x \in \chi} p(x) \log p(x)$$

The *differential entropy* $h(X)$ of a continuous random variable X with probability density function $f(x)$ is defined as

$$h(X) = -\int_S f(x) \log f(x) dx,$$

where S is the support set of the random variable.

Mutual information

Mutual information can be used to compare the performance of different communication techniques [16].

Definition:

The *mutual information* between two discrete random variables X and Y is

$$I(X,Y) = -\sum_{x \in X} \sum_{y \in Y} p(x,y) \log \frac{p(x,y)}{p(x)p(y)}$$

The *mutual information* between two continuous random variables X and Y is

$$I(X,Y) = -\int f(x,y) \log \frac{f(x,y)}{f(x)f(y)} dxdy$$

It can be obtained that [2]

$I(X,Y) = H(Y) - H(Y|X)$ for discrete random variables;

$I(X,Y) = h(Y) - h(Y|X)$ for continuous random variables.

Noise

The most common model for additive noise is Gaussian noise, as in the Gaussian channel. that is, the noise is white in spectrum and Gaussian distributed with zero mean in time domain. Gaussian distribution is very suitable for modeling the noise in radio links. [2,10]

Channel capacity

Information channel capacity is defined as

$$C = \max_{p(x)} I(X;Y),$$

where the maximum is taken over all possible input distributions $p(x)$.

With constraint on the average power, i.e., $E[X^2] \leq P$, where X is the transmitted signal, and P is the limitation on power, with a little abuse of notations, the information capacity is defined as

$C\ (P/N) = \max_{p(x):E[X^2] \leq P} I(X;Y)$, where N is the noise power.

Two-way channels

The two-way channel is illustrated in Fig. 1. In [2], Cover and Thomas mentioned that for the two nodes two transmit and receive simultaneously, sender 1 sends a codeword from the first codebook. Receiver 2 receives the sum of the codewords sent by the two senders plus some noise, and simply "subtracts" out the codeword of sender 2 to obtain a clean channel from sender 1 with only the influence of noise. However, in practice, implementing such subtraction in discrete channels in wireless networks is quite difficult, as illustrated in the following.

Digital Modulation

A digital modulator transforms discrete inputs into continuous waveform at a suitable frequency, and the corresponding demodulator transforms the continuous waveform back to discrete outputs. For example, BFSK (binary frequency shift keying) converts "0" into sinusoidal wave with frequency ω_c and "1" into sinusoidal wave with frequency $\omega_c + \Delta\omega$. An implementation of the demodulator is illustrated in Fig. 2. The demodulator will compare the output at the two frequencies and decides the output to be "0" or "1" [10].

Attenuation

Since the transmitter and receiver of a node are very close to each other, what is sent from a node will enter the its own receiver. We will refer to this phenomenon as "self-interference" in the following. The reason that self-interference is especially a serious problem in wireless communications is the attenuation of signals [3]. The average path loss is

$PL(d) \propto (d/d_0)^n$,

where n is the path loss exponent, d_0 is the reference distance, and d is the separation between the transmitter and the receiver. The path loss exponent n is 2 for free space, and can range from 3 to 6 for various multipath environments. Therefore, the magnitude of the signal sent from its own transmitter could be thousand times that of the signal from the other node. For example, for BFSK as in Fig. 2, the output of the envelope detector corresponding to the symbol sent from its own transmitter will be much larger than that corresponding to the symbol sent from the other transmitter. Therefore, what is obtained after the demodulator is determined by its own transmitter and independent of the other transmitter. In other words, the mutual information $I(X_i;Y_j) = H(Y_j)-H(Y_j|X_i) = H(Y_j)-H(Y_j) = 0$ $(i \neq j)$ if the two nodes are transmitting at the same time. Namely, it is impossible for the two nodes to transmit and receive successfully at the same time.

III. Channel capacity analysis and cancellation of self-interference

Discrete two-way channels

From the analysis in the previous section, the two nodes can not transmit and receive simultaneously in discrete two-way channels. Therefore, the capacity region is shown in Fig. 3, which could be approached by time-sharing or frequency-sharing duplexing. The total capacity C in both directions is the same as in one-way channel.

Waveform two-way channels

We will demonstrate that the mutual information with the knowledge of the self-interference is quite different from that without the knowledge of the self-interference. In the following, the limitation on average power is assumed.

A. Without the knowledge of self-interference

Without the knowledge of self-interference, for waveform two-way channels, if the two nodes attempt to transmit at the same time, the mutual information between the two nodes

$$I(X_i; Y_j) = h(Y_j) - h(Y_j|X_i) = h(X_i + X_j + Z_j) - h((X_i + X_j + Z_j)|X_i),$$

where $i \neq j$, and Z_j is the noise.

$$I(X_i; Y_j) = h(X_i + X_j + Z_j) - h((X_j + Z_j)|X_i) = h(X_i + X_j + Z_j) - h(X_j + Z_j),$$

since $X_j + Z_j$ are independent of X_i.

The entropy of noise [2, Example 9.1.2] is $h(Z_j) = [\log(2\pi eN)]/2$, where N is the noise power (variance). Also, the variance $E[(X_j + Z_j)^2] = E[X_j^2] + 2E[X_j]E[Z_j] + E[Z_j^2] = P_j + N$, where P_j is the power of X_j. since X_j and Z_j are independent and $E[Z_j] = 0$. Similarly, the variance $E[(X_i + X_j + Z_j)^2] = P_i + P_j + N$. To achieve the maximum mutual information in one-way channels, i.e., let the input also be Gaussian distributed, the maximum entropy of $X_j + Z_j$ is $\frac{1}{2}\log(2\pi e(P_j + N))$ and the maximum entropy of $Y_j = X_i + X_j + Z_j$ is $\frac{1}{2}\log(2\pi e(P_i + P_j + N))$ by [2, Theorem 9.6.5]. Therefore,

$$I(X_i; Y_j) = \frac{1}{2}\log(2\pi e(P_i + P_j + N)) - \frac{1}{2}\log(2\pi e(P_j + N)) = \frac{1}{2}\log(\frac{P_i + P_j + N}{P_j + N}) = \frac{1}{2}\log(1 + \frac{P_i}{P_j + N}).$$

Note that in this case, P_i (the received power of the signal from the other transmitter) << P_j (the power of the self-interference) because of the attenuation (path loss). Therefore, $I(X_i; Y_j)$ will be close to 0 in both directions. This consequence is the same as discrete two-way channels.

B. Using the knowledge of self-interference

With the knowledge of self-interference, i.e., given the signal from its own transmitter, for waveform two-way channels, if the two nodes attempt to transmit at the same time, the mutual information between the two nodes is

$$I((X_i; Y_j)| X_j) = h(Y_j | X_j) - h(Y_j | (X_i, X_j)) = h((X_i + X_j + Z_j)| X_j) - h((X_i + X_j + Z_j)|X_i, X_j),$$

where $i \neq j$, and Z_j is the noise.

$$I(X_i; Y_j) = h((X_i + X_j + Z_j)| X_j) - h((X_j + Z_j)|X_i, X_j) = h(X_i + Z_j) - h((X_j + Z_j)| X_j) = h(X_i + Z_j) - h(Z_j),$$

since X_i, X_j, and Z_j are independent.

The entropy of noise [2, Example 9.1.2] is $h(Z_j) = (\log 2\pi eN)/2$, where N is the noise power. Also, the variance $E[(X_j + Z_j)^2] = E[X_j^2] + 2E[X_j]E[Z_j] + E[Z_j^2] = P_j + N$, since X_j and Z_j are independent and $E[Z_j] = 0$. Then, to achieve the maximum mutual information in one-way channels [2], let the input be Gaussian distributed, the maximum entropy of $X_j + Z_j$ is $\frac{1}{2}\log(2\pi e(P_j + N))$ by [2, Theorem 9.6.5]. Therefore,

$$I(X_i; Y_j) = \frac{1}{2}\log(2\pi e(P_i + N)) - \frac{1}{2}\log(2\pi eN) = \frac{1}{2}\log(\frac{P_i + N}{N}) = \frac{1}{2}\log(1 + \frac{P_i}{N}).$$

This result is the same as that in one-way Gaussian channel. The capacity region is shown in Fig. 4, in which the communication in the two directions can be decomposed.

Cancellation of self-interference

Here we discuss some possible implementation issues of self-interference cancellation.

A possible implementation is illustrated in Fig. 5. The input from node i is transmitted through the transmitter antenna to the other node. The output from the other node is received through the receiver antenna. To subtract out the self-interference, we multiply the transmitted signal by an appropriate gain $-\alpha$ and then add it to the received signal. Then we can obtain the signal from the other node as if there is no self-interference. Of course, in practice, the complexity of the system might increase, and the gain α has to be calculated. How and where to implement the adder needs more detailed design.

Application of self-interference cancellation

Here we present some applications of self-interference cancellation. As mentioned, self-interference cancellation can be used in cellular network so that the forward-link and the reverse-link can use the same frequency at the same time, thus doubling the system capacity. Also, when two nodes have to communicate with each other directly without resorting to the base station in the ad-hoc mode of wireless local area networks [4], self-interference cancellation provides a bandwidth-efficient method. The time delay will also be shorter. Further, in local area network MAC (medium access control) protocols such as CSMA/CD (carrier sensing multiple access/ collision detection) [17], the nodes should detect the occurrence of collisions of packets and stop transmitting, resulting in shorter duration of a collision and higher efficiency. Such capability comes from the physical properties of cable, i.e., it is possible to listen to the cable while transmitting [17]. However, in wireless communications, the nodes usually did not have such capability because of the strong self-interference. Now, with self-interference cancellation, detection of collision becomes possible. That is, a node can know whether or not other nodes are transmitting by filtering out its own interference. Thus, self-interference cancellation is also promising in improving the design and performance of protocols.

IV. Discussions and Conclusions

Two-way channels have found wide applications with the development of wireless communications. In this paper, we examine the capacity of not only discrete but also waveform two-way wireless channels by information theory.

For discrete two-way channels, we find that the sum of the capacity in each direction is the same as that of one-way channels. This is due to the attenuation of signals with distance in wireless communications. If the two nodes transmit information simultaneously, the signal transmitted from the other end of the channel will have a very small power level compared with that of the signal transmitted from its own transmitter. Furthermore, with the quantization at the demodulator, the decoded symbols are determined by what the symbols transmitted by itself, and a node cannot obtain any information about the other node. For waveform channels without the knowledge of self-interference, the sum of the capacity in each direction is still the same as that of one-way channels due to the signal attenuation. However, with the knowledge of self-interference, the capacity of a two-way waveform channel can be increased to be twice that of a one-way channel. That is, unlike two-way discrete channels, self-interference can be cancelled on a two-way waveform channel. A possible implementation of such self-interference cancellation is illustrated in this paper. The results in this paper echo with the decomposability in [2] and verify the ideas in [18].

Two-way channels are very important not only in duplexing in cellular networks and peer-to-peer communication in wireless local area networks, but also in multiple access protocols. We indicated that self-cancellation can be a way to implement the collision detection in wireless local area networks, which is quite difficult to implement in usual situation without self-interference cancellation due to again the signal attenuation.

This paper shows that considering both physical layer and networking layer is very important. For future work, more consideration of physical layer [11], such as multipath fading [3], can be investigated. Also, efficient implementation of self-interference should be developed. Moreover, the performance of multiple-access protocols such as CSMA/CD implemented by self-interference cancellation can be investigated. Other applications of two-way channels in multiaccess communications and multihop networks can also be studied.

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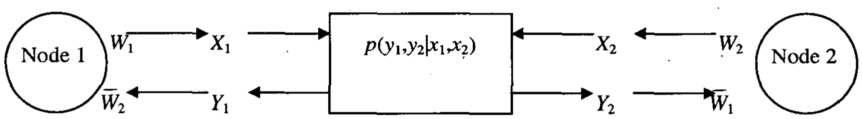

Fig. 1 the two-way channel

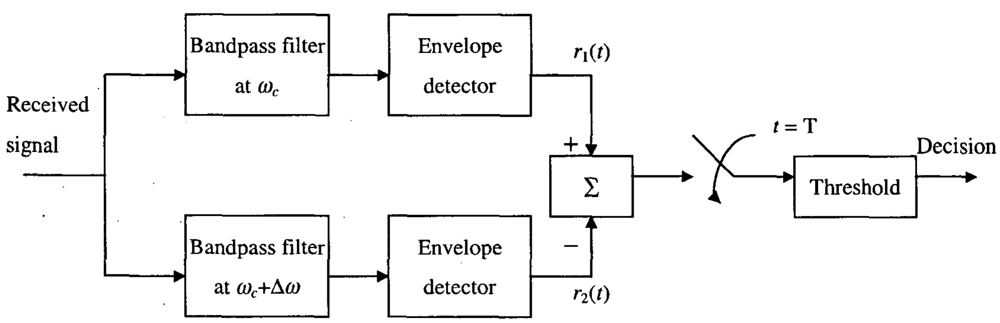

Fig. 2 demodulator for incoherent FSK

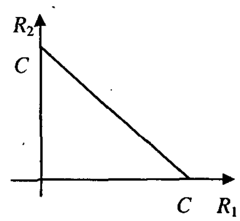

Fig. 3 capacity region of two-way channels without the knowledge of self-interference

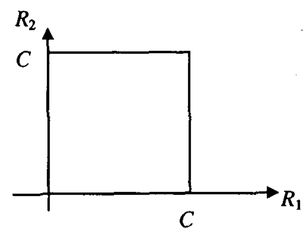

Fig. 4 capacity region of two-way channels with the knowledge of self-interference

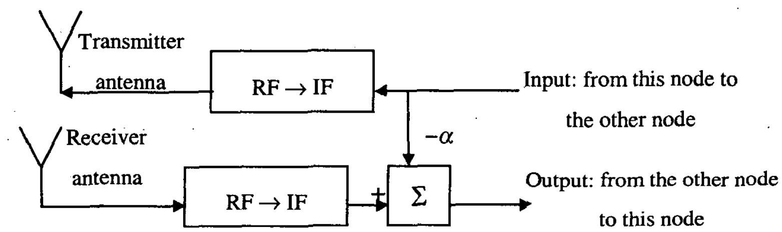

Fig. 5 illustration of an implementation of self-interference cancellation