Virtual Full-Duplex Wireless Communication via Rapid On-Off-Division Duplex

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Abstract—This paper introduces a novel paradigm for design-ing the physical and medium access control (MAC) layers of mobile ad hoc or peer-to-peer networks formed by half-duplex radios. A node equipped with such a radio cannot simultaneously transmit and receive useful signals at the same frequency. Unlike in conventional designs, where a node's transmission frames are scheduled away from its reception, each node transmits its signal through a randomly generated on-off *duplex mask (or signature)* over every frame interval, and receive a signal through each of its own off-slots. This is called *rapid on-off-division duplex (RODD)*. Over the period of a single frame, every node can transmit a message to some or all of its peers, and may simultaneously receive a message from each peer. Thus RODD achieves virtual full-duplex communication using half-duplex radios and can simplify the design of higher layers of a network protocol stack significantly. The throughput of RODD is evaluated under some general settings, which is significantly larger than that of ALOHA. RODD is especially efficient in case the dominant traffic is simultaneous broadcast from nodes to their one-hop peers, such as in spontaneous wireless social networks, emergency situations or on battlefield. Important design issues of peer discovery, distribution of on-off signatures, synchronization and error-control coding are also addressed.

Index Terms—Ad hoc network, half-duplex, multiaccess chan-nel, neighbor discovery, random access, wireless peer-to-peer networks.

I. INTRODUCTION

In spite of decades of advances in wireless and networking technologies, to design a functional and reliable mobile ad hoc or peer-to-peer network remains enormously challenging [1]. The main roadblocks include the difficult nature of the wireless medium and the mobility of wireless terminals, among others. A crucial constraint on wireless systems is the *half-duplex* nature of affordable radios, which prevents a radio from receiving any useful signal at the same time and over the same frequency band within which it is transmitting. The physical reason is that during transmission, a radio's own signal picked up by its receive antenna is typically orders of magnitude stronger than the signals from its peers, such that the desired signals are lost due to the limited dynamic range of the radio frequency (RF) circuits. The half-duplex constraint has far-reaching consequences in the design of wireless networks: The uplink and downlink transmissions in any cellular-type network are separated using time-division duplex (TDD) or frequency-division duplex (FDD); standard designs of wireless

ad hoc networks schedule transmission frames of a node away from the time and frequency slot over which the node receives data [2].

In this work, the half-duplex constraint is addressed at a fundamental level, which is that the received signal of a half-duplex node is *erased* during periods of its own active transmission. We recognize that, it is neither necessary nor efficient to separate the transmission slots and listening slots of a node in the timescale of a frame of hundreds or thousands of symbols as in TDD. We propose for the first time a technique called *rapid on-off-division duplex (RODD)*. The key idea is to let each node transmit according to a unique *on-off duplex mask (or signature)* over a frame of symbols or slots, so that the node can receive useful signals from its peers during the *off-slots* interleaved between its *on-slot* transmissions. Importantly, all nodes may send (error-control-coded) information simultaneously over a frame interval, as long as the masks of peers are sufficiently different, so that a node receives enough signals during its off-slots to decode information from its peers. Over the period of a single frame, every node simultaneously broadcasts a message to some or all other nodes in its neighborhood, and may receive a message from every neighbor at the same time.

Switching the carrier on and off at the timescale of one or several symbols is feasible, thanks to the sub-nanosecond response time of RF circuits. In fact, on-off signaling over sub-millisecond slots is used by time-division multiple-access (TDMA) cellular systems such as GSM. Time-hopping im-pulse radio transmits on and off at nanosecond intervals [3], which is orders of magnitude faster than needed by RODD (in microseconds). Moreover, receiving signals during one's own off-slots avoids self-interference and circumvents the dynamic range issue which plagues other full-duplex schemes, such as code-division duplex (CDD) [4], [5].

Ad hoc networks using rapid on-off-division duplex have unique advantages: 1) RODD enables virtual full-duplex trans-mission and greatly simplifies the design of higher-layer proto-cols. In particular, "scheduling" is carried out in a microscopic timescale over the slots, so that there is no need to separate transmitting and listening frames; 2) RODD signaling takes full advantage of the superposition and broadcast nature of the wireless medium. As we shall see, the throughput of a RODD-based network is greater than that of ALOHA-type random access, and is more than twice as large as that

of slotted ALOHA in many cases; 3) RODD signaling is particularly efficient when the traffic is predominantly peer-to-peer broadcast, such as in mobile systems used in local advertising, spontaneous social networks, emergency situations or on battlefield; 4) Communication overhead usually comes as an afterthought in network design, whereas RODD enables extremely efficient exchange of a small amount of state information amongst neighbors; 5) Because nodes simultaneously transmit, the channel-access delay is typically smaller and more stable than in conventional reservation or scheduling schemes.

This paper presents a preliminary study of several aspects of RODD. Related work and technologies are discussed in Section II. Mathematical models of a network of nodes with synchronous RODD signaling is presented in Sections III. Assuming mutual broadcast traffic, the throughput of a fully-connected, synchronized, RODD-based network is studied in Section IV. Design issues such as duplex mask assignment, peer discovery, error-control codes and synchronization are discussed in Sections V–VII. We conclude the paper with a discussion of applications of RODD in Section VIII.

II. RELATED WORK

There have been numerous works on the design of physical and MAC layers for wireless networks (see the surveys [6]–[8] and references therein). Two major challenges need to be addressed: One is the half-duplex constraint; the other is the broadcast and superposition nature of the wireless medium, so that simultaneous transmissions interfere with each other at a receiver. State-of-the-art designs either schedule nodes orthogonally ahead of transmissions, or apply an ALOHA-type random access scheme, or use a mixture of random access and scheduling reservation [9]. Typically, the *collision model* is assumed, where if multiple nodes simultaneously transmit, their transmissions fail due to collision at the receiver. Under such a model, random access leads to poor efficiency (e.g., ALOHA's efficiency is less than $1/e$). On the other hand, scheduling node transmissions is often difficult and subject to the hidden terminal and exposed terminal problems.

Despite the half-duplex constraint, it is neither necessary nor efficient to separate a node's transmission slots and listening slots in the timescale of a frame. In fact, time-sharing can fall considerably short of the theoretical optimum. For example, it has been shown that the capacity of a cascade of two noiseless binary bit pipes through a half-duplex relay is 1.14 bits per channel use [10], [11], which far exceeds the 0.5 bit achieved by TDD and even the 1 bit upper bound on the rate of binary signaling. This is because non-transmission can be regarded as an additional symbol for signaling (besides 0 and 1), whose positions can be used to communicate information (see also [12]).

Several recent works on the implementation of physical and MAC layers break away from the collision model and single-user transmission. For example, superposition coding for degraded broadcast channels has been implemented using software-defined radios [13]. Analog network coding has also been implemented based on 802.11 technology [14], where, when two senders transmit simultaneously, their packets collide, or more precisely, superpose at the receiver, so that if the receiver already knows the content of one of the packets, it can cancel the interference and decode the other packet. Similar ideas have been proven feasible in some other contexts to achieve interference cancellation in unmanaged ZigBee networks [15], ZigZag decoding for 802.11 in [16], and interference alignment and cancellation in [17].

Rapid on-off-division duplex is related to code-division duplex, which was proposed in the context of code-division multiple access (CDMA) [4]. In CDD, orthogonal (typically antipodal) spreading sequences are allocated to uplink and downlink communications, so that a receiver ideally cancels self-interference by matched filtering with its own receive spreading sequence. Despite the claimed higher spectral efficiency than that of TDD and FDD in [5], CDD is not used in practice because it is difficult to maintain orthogonality due to channel impairments and suppress self-interference which is orders of magnitude stronger than the desired signal. In RODD, the desired signal is sifted through the off-slots of the transmission frame, so that the leakage of the transmit energy into the received signal is kept to the minimum.

RODD can also be viewed as (very fast) TDD with irregular symbol-level transition between transmit and receive slots as well as coding over many slots. Although on-off signaling can in principle be applied to the frequency domain, it would be much harder to implement sharp band-pass filters to remove self-interference.

The RODD signaling also has some similarities to that of time-hopping impulse radio [18], [19]. Both schemes transmit a sequence of randomly spaced pulses. There are crucial differences: Each on-slot (or pulse) in RODD spans one or a few data symbols (in microseconds), whereas each pulse in impulse radio is a baseband monocycle of a nanosecond or so duration. Moreover, impulse radio is carrier-free and spreads the spectrum by many orders of magnitude, whereas RODD uses a carrier and is not necessarily spread-spectrum.

III. MODELS AND RODD SIGNALING

Consider an ad hoc network consisting of K nodes, indexed by $1, \ldots, K$. Suppose all transmissions are over the same frequency band. Suppose for simplicity each slot is of one symbol interval and all nodes are perfectly synchronized over each frame of M slots. Let the binary on-off duplex mask of node k over slots 1 through M be denoted by $\boldsymbol{s}_k = [s_{k1}, \ldots, s_{kM}]$. During slot m, node k may transmit a symbol if $s_{km} = 1$, whereas if $s_{km} = 0$, the node listens to the channel and emits no energy.

A. The Fading Channel Model

The physical link between any pair of nodes is modeled as a fading channel. Let the path loss satisfy a power law with exponent α. The received signal of node k during each slot

$m \in \{1, \ldots, M\}$ is described by

$$Y_{km} = (1 - s_{km}) \sum_{j \neq k} \sqrt{\gamma_j} d_{kj}^{-\alpha/2} h_{kj} s_{jm} X_{jm} + W_{km} \quad (1)$$

where d_{kj} denotes the distance between nodes k and j, h_{kj} denotes the fading coefficient, X_{jm} denotes the transmitted symbol of node j at time slot m, W_{km} denotes additive noise, and γ_j denotes the signal-to-noise ratio (SNR) of node j at unit distance without fading. The received signal of each node over its own off-slots is the superposition of the signals from its peers over those slots (in addition to noise). Thus RODD forms fundamentally a *multiaccess channel with erasure.*

Let us also assume that the signaling of each node is subject to unit average power constraint, i.e., for every $k = 1, \ldots, K$, every codeword $(x_{k1}, \ldots, x_{kM})$ satisfies $\sum_{m=1}^{M} s_{km} x_{km}^2 \leq M$. The SNR of the link from node j to node k can be regarded as $\gamma_{kj} = \gamma_j \, d_{kj}^{-\alpha} |h_{kj}|^2$. We say node j is a (one-hop) *neighbor* or a *peer* of node k if γ_{kj} exceeds a given threshold.[1] Let the set of neighbors (or peers) of k be denoted as ∂k, which is also called its *neighborhood*. We are only interested in communication over links between neighbors. The model (1) can be reduced to

$$Y_{km} = (1 - s_{km}) \sum_{j \in \partial k} \sqrt{\gamma_j} d_{kj}^{-\alpha/2} h_{kj} s_{jm} X_{jm} + V_{km} \quad (2)$$

where V_{km} consists of the additive noise W_{km} as well as the aggregate interference caused by non-neighbors.

Note that (1) and (2) model the half-duplex constraint at a fundamental level: If node k transmits during a slot, then its received signal during the slot is erased.

B. A Deterministic Model

It is instructive to consider a simplification of the preceding models by assuming noiseless non-coherent reception and energy detection. That is, as long as some neighbor transmits energy during an off-slot of node k, a "1" is observed in the slot, whereas if no neighbor emits energy during the slot, a "0" is observed. This can be described as an *inclusive-or* multiaccess channel (referred to as OR-channel) with erasure:

$$\hat{Y}_{km} = (1 - s_{km}) \left(\vee_{j \in \partial k} (s_{jm} Z_{jm}) \right) \quad (3)$$

for $m = 1, \ldots, M$, where the binary inputs Z_{jm} and outputs $\hat{Y}_{km}$ take values from $\{0, 1\}$. Since the output is a deterministic function of the inputs, (3) belongs to the family of *deterministic models*, which have been found to be a very effective tool in understanding multiuser channels (see, e.g, [20], [21]). Despite its simplicity, it captures the superposition nature of the physical channel, while ignoring the effect of noise and interference, although those impairments can also be easily included in the model.

Fig. 1 illustrates a snapshot of RODD signals of four nodes taken over 50 slots. Here $\underline{Z}_1, \ldots, \underline{Z}_4$ represent the transmitted signals of node 1 through node 4, respectively, where the solid

[1]The neighbor relationship is not necessarily reciprocal because $\gamma_j |h_{kj}|^2$ and $\gamma_k |h_{jk}|^2$ need not be identical.
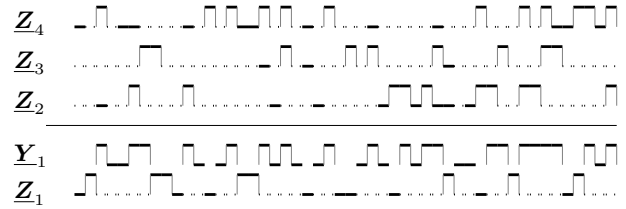

Fig. 1.   RODD signaling over an OR-channel with erasure.

lines represent on-slots and the dotted lines represent off-slots. The received signal of node 1 through its off-slots is $\underline{Y}_1$, which is the superposition of $\underline{Z}_2$, $\underline{Z}_3$, and $\underline{Z}_4$ with erasures at its own on-slots (represented by blanks). Over the period of a single RODD frame, every node can "simultaneously" broadcast a message to its neighbors and receive a message from every neighbor at the same time.

IV. THROUGHPUT RESULTS

Suppose each node has a message to broadcast to all its (one-hop) neighbors by transmitting a frame over M slots. An M-slot frame is regarded as being successful for a given node if its message is decoded correctly by all neighbors; otherwise the frame is in error. A rate tuple for the K nodes is achievable if there exists a code using which the nodes can transmit at their respective rates with vanishing error probability in the limit where the frame length $M \to \infty$.

The achievable rates obviously depends on the network topology and the duplex masks. It is assumed that every node has complete knowledge of the duplex masks of all peers (see Section V on neighbor discovery). For simplicity, in Sections IV-A and IV-B, we first consider a symmetric network of K nodes who are neighbors of each other, where the gain between every pair of nodes is identical. Suppose the elements s_{km} of the duplex masks are independent identically distributed (i.i.d.) Bernoulli random variables with $\mathsf{P}(s_{km} = 1) = q$.

In the simplest scenario, all nodes use randomly generated i.i.d. codebooks dependent on the parameters (K, M, q) but independent of the duplex masks otherwise. Such a code is called a *signature-independent code*. Alternatively, nodes may use *signature-dependent codes*, where the codebooks may depend on the signature pattern $\boldsymbol{S}_m = \{s_{1m}, s_{2m}, \ldots, s_{Km}\}$ in every slot m. Since all nodes are symmetric, dependence on the signatures is only through the weight of the pattern $\boldsymbol{S}_m$.

The amount of information that a node can transmit during a frame is an increasing function of the number of on-slots, which in turn has a negative impact on the amount of information it can collect. If the amount of information a node receives is several times of the amount of information it transmits, its signature should consist of many more off-slots than on-slots, i.e., it is somewhat sparse.

In case all messages from different nodes are of the same number of bits, the rate tuple collapses to a single number. The maximum achievable such rate by using signature-independent

(resp. signature-dependent) codes is called the *symmetric rate* (resp. *symmetric capacity*).

A. The Deterministic Model

Consider the OR-channel described by (3). A node's codeword is basically erased by its own signature mask before transmission.

Proposition 1: The symmetric rate and the symmetric capacity of the OR-channel (3) are

$$R = \max_{p \in [0,1]} \frac{1}{K-1} \sum_{n=1}^{K-1} \binom{K-1}{n} q^n (1-q)^{K-n} H_2(p^n) \quad (4)$$

$$C = \frac{1}{K-1} \left[(1-q) - (1-q)^K \right] \quad (5)$$

where $H_2(p) = -p \log p - (1-p) \log(1-p)$ is the binary entropy function.

The detailed proof is omitted due to space limitations. The symmetric rate is achieved by random codebooks with i.i.d. Bernoulli$(1-p)$ entries where p maximizes (4). To see this, consider any given signature pattern $\boldsymbol{S}_m = \boldsymbol{s}$ in slot m, in which n nodes transmit while the remaining $K-n$ of them listen, the contribution of the slot to the achievable rate is then given by the mutual information between the binary received signal Y and the transmitted symbols $\underline{\boldsymbol{Z}}$ in the slot:

$$I(\underline{\boldsymbol{Z}}; Y | \boldsymbol{S}_m = \boldsymbol{s}) = H(Y | \boldsymbol{S}_m = \boldsymbol{s}) - H(Y | \underline{\boldsymbol{Z}}, \boldsymbol{S}_m = \boldsymbol{s})$$
$$= H(Y | \boldsymbol{S}_m = \boldsymbol{s}) \quad (6)$$
$$= H_2(p^n) \quad (7)$$

where the second equality is due to the deterministic nature of the model.

The symmetric capacity is higher than the symmetric rate because there is gain to adapt the codebooks to the signatures. Basically the codebook entries at each slot are generated as independent Bernoulli random variables whose mean value depends on the number of transmitting nodes in the slot (aka the weight of $\boldsymbol{S}_m$). The parameters of the Bernoulli variables can be optimized for achieving the capacity.

We next compare the throughput of a RODD-based scheme with that of ALOHA-type random access schemes over the same channel (3), where the throughput is defined as the sum rate of all nodes. During each frame interval (or contention period), every node in ALOHA independently chooses either to transmit (with probability q) or to listen (with probability $1-q$) and the choices are independent across contention periods. A node successfully broadcasts its message to all other nodes if the frame is the only transmission during a given frame interval. It is easy to see that the throughput of the system with ALOHA is $Kq(1-q)^{K-1}$, which achieves the maximum $(1-1/K)^{K-1}$ with $q = 1/K$.

For three different node populations ($K = 3, 5, 20$), the comparison between RODD and ALOHA is shown in Fig. 2. The sum symmetric rate achieved by signature-independent codes is plotted for RODD. Clearly, the maximum throughput of RODD is much higher than that of ALOHA, where the gap increases as the number of nodes increases. In fact the
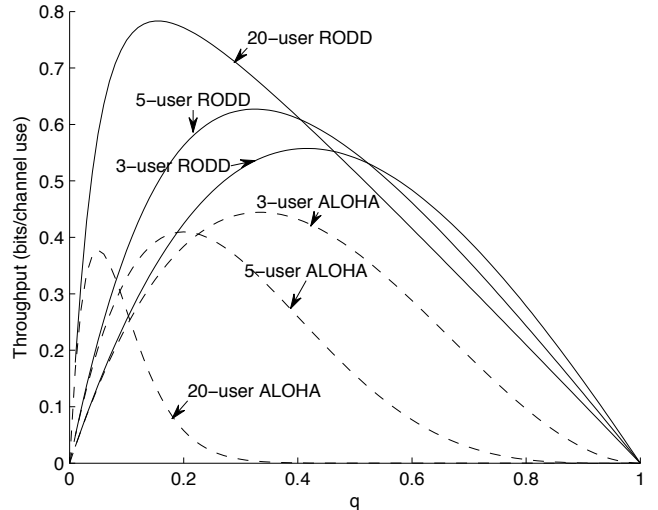

Fig. 2. Comparison of the throughput of RODD and ALOHA over OR-channel.

throughput of RODD exceeds that of ALOHA for all values of q. In case of a large number of nodes, the throughput of ALOHA approaches $1/e$. On the other hand, with $p = 1 - 2^{-\frac{1}{(K-1)q}}$, the total throughput achieved by using RODD signaling approaches $1 - q$ as $K \to \infty$, which is also the asymptotic sum capacity of RODD achieved by signature-dependent codes.

The reason for the inferior performance of ALOHA is largely due to packet retransmissions after collision. Even if multi-packet reception is allowed, the throughput of ALOHA is still far inferior compared to RODD signaling due to the half-duplex constraint. This is because, in the case of broadcast traffic studied here, if two nodes simultaneously and successfully transmit their packets to all other nodes, they still have to exchange their messages using at least two additional transmissions.

B. The Gaussian Multiaccess Channel

Consider now a (non-fading) Gaussian multiaccess channel described by (1), where $d_{kj} = 1$, $h_{kj} = 1$ for all k, j, and $\{W_{ji}\}$ are i.i.d. Gaussian random variables. For simplicity, let all nodes be of the same SNR, $\gamma_j = \gamma$. Let the average power of each transmitted codeword be 1. Since each node only transmits over about qM slots, the average SNR during each active slot is essentially γ/q.

It is easy to see that the throughput of ALOHA over the Gaussian channel is $Kq(1-q)^{K-1}g(\gamma/q)$, where $g(x) = \frac{1}{2}\log(1+x)$. Similar to the results for the deterministic model, we can show that the symmetric rate and the symmetric capacity for the Gaussian multiaccess channel are achieved with Gaussian codebooks by signature-independent codes and signature-dependent codes, respectively:

Proposition 2: The symmetric rate and the symmetric capacity of the non-fading Gaussian multiaccess channel de-
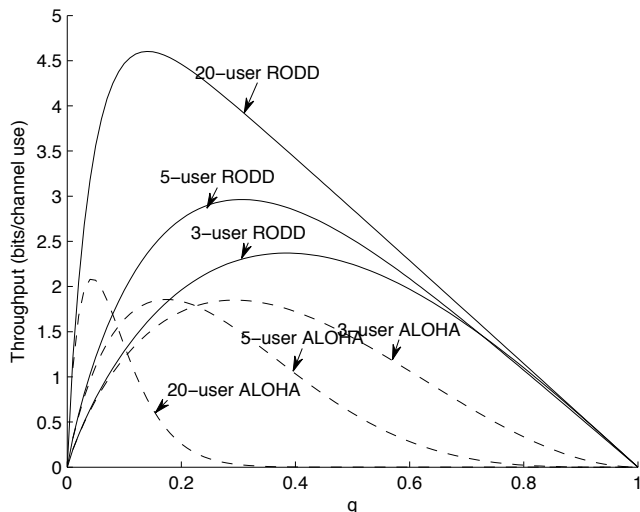
Fig. 3. Comparison of the throughput of RODD and ALOHA over Gaussian multiaccess channel at SNR $\gamma = 20$ dB.

scribed by (1) are

$$R = \frac{1}{K-1} \sum_{m=1}^{K-1} \binom{K-1}{m} q^m (1-q)^{K-m} g\left(\frac{m\gamma}{q}\right) \quad (8)$$

$$C = \frac{1}{K-1} \sum_{m=1}^{K-1} \binom{K-1}{m} q^m (1-q)^{K-m} g(w_m) \quad (9)$$

where $w_m = \max(\frac{K-m}{K-1} v - 1, 0)$ and v is chosen to satisfy

$$\frac{1}{K} \sum_{m=1}^{K-1} \binom{K}{m} q^m (1-q)^{K-m} w_m = \gamma . \quad (10)$$

The case of signature-dependent codes can be regarded as allocating different powers to different signature patterns in a parallel Gaussian multiaccess model. As is shown in Fig. 3, the throughput of RODD with signature-independent codes is higher than that of ALOHA for all number of nodes and every value of q. The more nodes in the network, the more advantage of RODD signaling.

C. The Achievable Asymmetric Rates

In many applications, the amount of data different nodes transmit/broadcast can be very different. In random access schemes, nodes with more data will contend for more resources. The data rate, transmit power and modulation format of a RODD-based codebook can be adapted to the amount of data to be transmitted.

Suppose the elements s_{km} of node k's signature are i.i.d. Bernoulli random variables with $\mathsf{P}(s_{km} = 1) = q_k$. Here we study the asymmetric rate region of RODD achieved by signature-independent codes under the fading channel model described in (1).

Proposition 3: The rate tuple $(R_1, \ldots, R_K)$ is achievable over the fading channel (1) if

$$R_k \leq \min_{i \neq k} (1 - q_i) \sum_{\mathcal{A} \subseteq \mathcal{K} \setminus \{i\}, k \in \mathcal{A}} \frac{\gamma_{ik}}{q_k h_{\mathcal{A}}^i} g(h_{\mathcal{A}}^i) \prod_{j \in \mathcal{A}} q_j \prod_{l \notin \mathcal{A}} (1 - q_l) \quad (11)$$

for $1 \leq k \leq K$, where $\mathcal{K} = \{1, 2, \ldots, K\}$ and $h_{\mathcal{A}}^i$ is defined as $h_{\mathcal{A}}^i = \sum_{j \in \mathcal{A}} \frac{\gamma_{ij}}{q_j}$.

Similar as discussed in the case for the Gaussian Multiaccess channel, the asymmetric rate tuple given in (11) can be achieved by signature-independent codes with random Gaussian codebooks.

V. SIGNATURE DISTRIBUTION AND PEER DISCOVERY

It is not necessary to directly distribute the set of K duplex masks to each node in the network. It suffices to let nodes generate their signatures using the same pseudo-random number generator or some other deterministic function with their respective unique network interface address (NIA) as the seed. Every node can in principle reconstruct all signatures by enumerating all NIAs.

Before establishing data links, a node needs to acquire the identities or NIAs of its neighbors. This is called *neighbor discovery*. Conventional discovery schemes are based on random access, where each node transmits its NIA many times with random delay, so that after enough transmissions, every neighbor receives it at least once without collision [22]–[24]. As we shall see next, network-wide full-duplex discovery is achievable using RODD signaling, where all nodes simultaneously send their (sparse) on-off signatures and make measurements through their respective off-slots.

The linear multiaccess channel model (1) applies to the neighbor discover problem if X_{jm}, $m = 1, \ldots, M$, are replaced by the same indicator variable B_j, where $B_j = 1$ if node j is present in the neighborhood, and $B_j = 0$ otherwise. The signal each node k transmits over the entire discovery period to identify itself is then the signature s_k (this signature need not be the same or of the same length as the one used for data communication). Take node 1, for example, whose observation made through its off-slots can be expressed (using a simplification of model (1)) as a vector

$$\boldsymbol{Y} = \sum_{k=2}^{K} X_k \boldsymbol{s}_k + \boldsymbol{W} \quad (12)$$

where X_k (which incorporates fading and path loss) is zero or is close to zero except if node k is in the neighborhood of node 1 and transmits $\boldsymbol{s}_k$ during the off-slots of user 1. The vector $[X_1, \ldots, X_K]$ is typically extremely sparse.

In [25], [26], Luo and Guo have pointed out that to identify a small number of neighbors out of a large collection of nodes based on the signal received over a linear channel is fundamentally a *compressed sensing (or sparse recovery)* problem, for which a small number of measurements (channel uses) suffice [27], [28].[2] Using *pseudo-random on-off signatures* for neighbor discovery was proposed in [25], [26] along

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[2]Several authors have studied user activity problem in cellular networks using multiuser detection techniques [29]–[31]. These works assume channel coefficients are known to the receiver, which is not the case in most networks.

with a group testing algorithm. The key observation is that, from one node's viewpoint, for each slot with (essentially) no energy received, all nodes who would have transmitted a pulse during that slot cannot be a neighbor. A node basically goes through every off-slot and eliminates nodes incompatible with the measurement; the surviving nodes are then regarded as neighbors. The compressed neighbor discovery scheme requires only noncoherent energy detection and has been shown to be effective and efficient at moderate SNRs; moreover, it requires many fewer symbol transmissions than conventional neighbor discovery schemes.

With improvement over the algorithms of [26], numerical examples show that in a network of $N = 10,000$ Poisson-distributed nodes, where each node has on average 50 neighbors, 99% discovery accuracy is achieved using 2,500-bit signatures at moderate SNR, less than half of that needed by random access discovery to achieve the same accuracy. Only one frame of transmission is needed here, as opposed to many frames in the case of random access, thus offering significant additional reduction of timing and error-control overhead embedded in each frame.

Since RODD transmission and neighbor discovery share the same linear channel model, it is possible for a new node in a neighborhood to carry out neighbor discovery solely based on a frame of data transmission by all peers over the multiaccess channel, without an explicit neighbor discovery phase.

VI. CHANNEL CODING FOR RODD

A. Capacity-achieving Codes

From individual receiver's viewpoint, the channel with RODD is a multiaccess channel with erasure at known positions. All good codes for multiaccess channels are basically good for RODD. Coding schemes for the OR multiaccess channel have been studied, e.g., in [32] and [33]. In particular, the nonlinear trellis codes of [33] achieves about 60% of the sum-capacity.

Coding for the Gaussian multiaccess channel is well-understood. In particular, Gaussian codebooks achieve the capacity. In practice, however, QAM or PSK signaling is often used depending on the SNR. Practical codes have been shown to be effective in [34]–[36]. For example, the codes of [34] is based on LDPC codes, where it is pointed out that degree optimization for the multiuser scenario is important in this case. Reference [36] is based on trellis-coded multiple access, which can be particularly suitable for higher constellations. There has also been study on rateless codes for multiaccess channels, e.g., [37], [38].

Also relevant is a large body of works on channel codes for code-division multiple access (CDMA). By regarding spreading and channel code as the inner and outer codes, respectively, turbo decoding has been found to be highly effective for such systems [39]. In the case of RODD, the on-off signatures and individual node's channel code and can be viewed as inner and outer codes, which suggests that turbo decoding can be highly effective.

B. A Simple, Short Code Based on Sparse Recovery

A simple channel code for RODD is proposed in [40], which does not achieve the capacity but is simple and efficient if the messages exchanged between peers consist of a relatively small number of bits.

As in the peer discovery problem, decoding of this simple code is essentially via sparse recovery. Consider the simplest case, where each node has one bit to broadcast to all other nodes. Let node k be assigned two on-off signatures so that the node transmits $s_{k,1}$ to send message "1," and transmits $s_{k,0}$ to send message "0." All nodes transmit their signatures simultaneously, and listen to the channel through their respective off-slots. Clearly, this is similar to the neighbor discovery problem, except that each node tries to identify which signature from *each* neighbor was transmitted so as to recover 1 bit of information from the node.

The preceding coding scheme can be easily extend to the case where the message m_k from node k is chosen from a small set of messages $\{1, \ldots, \mu\}$. In this case, node k is assigned μ distinct on-off signatures, and transmit the signature corresponding to its message. All signatures are known to all nodes. The problem is now for each node to identify, out of a total of μK messages (signatures) from all nodes, which K messages (signatures) were selected. For example, in case of 10 nodes each with a message of 10 bits, the problem is to identify 10 out of $10 \times 2^{10} = 10,240$ signatures. A rich set of efficient and effective decoding algorithms are studied in [40].

VII. SYNCHRONIZATION

In order to decode the messages from the neighboring nodes, it is crucial not only to acquire their signatures, but also their timing (or relative delay). Acquisition of timing is in general a prerequisite to decoding data regardless of what physical- and MAC-layer technologies are used, thus RODD is not at a disadvantage compared to other schemes. In a RODD system, nodes with data may transmit over every frame, providing abundant cues for timing acquisition and synchronization. Timing acquisition and decoding are generally easier if the frames arriving at a receiver are fully synchronous locally within each neighborhood. To maintain synchronicity in a dynamic network requires extra overhead. Synchronization is, however, not a necessity. Synchronous or not, each node collects essentially the same amount of information through its own off-slots.

A. Synchronous RODD

Synchronicity has been studied extensively in the context of ad hoc and sensor networks. Various distributed algorithms for reaching consensus [41], [42] can be applied to achieve local synchronicity, e.g., by having each node shift its timing to the "center of gravity" of the timings of all nodes in the neighborhood. The timing still fluctuates over the network, but is a smooth function geographically. The accuracy of synchronization is limited by two factors: the channel impairments and the propagation delay. Synchronization is easy if a RODD slot can be much longer than the propagation delay across the

diameter of a neighborhood. For example, a slot interval of 100 μs would be 100 times the propagation time of 1 μs over a 300-meter range. For high-rate communication, a RODD symbol can be in the form of an orthogonal frequency division multiplexing (OFDM) symbol.

Local synchronicity can also be achieved using a common reference, such as a strong beacon signal. A possible shortcut is to have all nodes synchronized using GPS or via listening to base stations in an existing cellular network, if applicable.

B. Asynchronous RODD

In an asynchronous design, the relative delay can be arbitrary, so that the off-slot of a node is in general not aligned with the on-slot of its neighbors. Techniques for decoding asynchronous signals developed in the context of multiuser detection/decoding [43], [44] are generally applicable to RODD-based systems.

The algorithms for timing acquisition and synchronization should account for the fact that an active node can only observe each frame partially through its off-slots. To infer about the delays of neighbors based on partial observations is fundamentally the filtering of a hidden Markov process.

VIII. CONCLUDING REMARKS

Proposed and studied in this paper is the novel *rapid on-off-division duplex* scheme, which suggests a radically different design than conventional FDD and TDD systems. On-off signaling has been used since the early days of telegraphy, and is also the basis for a simple modulation scheme known as on-off keying. Frequency-hopping multiple-access can be regarded as a form of on-off signaling in the frequency domain. Recently, transmission through a random on-off mask has been suggested to control the amount of interference caused to other nodes in an interference channel [45]. RODD is unique in that it exploits on-off signaling to achieve virtual full-duplex communication using half-duplex radios.

It is interesting to note that FDD and TDD suffice in cellular networks because uplink and downlink transmissions can be assigned regular orthogonal resources. This absolute separation of uplink and downlink does not apply to peer-to-peer networks because, in such a network, one node's downlink resource has to be matched with its peer's uplink. The prevalence of FDD- and TDD-like scheduling schemes in current ad hoc networks is in part inherited from the more mature technologies of wired and cellular networks, and due to the difficulty of separating superposed signals. Advances in multiuser detection and decoding (e.g., [46]) and recent progress in sparse recovery have enabled new technologies that break away from the model of packet collisions, and hence set the stage for RODD-based systems.

A rich class of results and techniques in network information theory apply to RODD-based systems. Moreover, almost all technological advances in the wireless communications are also applicable to such systems, including OFDM, multiple antennas, relay, cooperation, to name a few. In particular, RODD signaling enables virtual full-duplex relaying, where a

relay forwards each received symbol in the next available on-slot. The queueing delay at a relay can be all but eliminated. This is in contrast to the store-and-forward scheme used by half-duplex relays, where the queueing delay at a relay is of the length of one or several frames.

We conclude this paper by describing a specific advantage of RODD for network state information exchange. Many advanced wireless transmission techniques require knowledge of the state of communicating parties, such as the power, modulation format, beamforming vector, code rate, acknowledgment (ACK), queue length, etc. Conventional schemes often treat such *network state information* similarly as data, so that exchange of such information require a substantial amount of overhead and, in ad hoc networks, often many retransmissions. In a highly mobile network, the overhead easily dominates the data traffic [1]. By creating a virtual full-duplex channel, RODD is particularly suitable for nodes to efficiently broadcast local state information to their respective neighbors. In fact RODD can be deployed as a new sub-layer of the protocol stack, solely devoted to (virtual full-duplex) state information exchange. One potential application of this idea is to assist distributed scheduling by letting each node choose whether to transmit based on its own state and the states of its neighbors. We have shown that a simple distributed protocol lead to an efficient network-wide TDMA schedule, which typically doubles the throughput of ALOHA [47]. Another application is distributed interference management by exchanging interference prices as studied in [48].

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