Reliability and Longer Range for Low Power Transmitters with On Demand Network MIMO

Mary Ann Weitnauer*, Qiongjie Lin*, Huanyu Zhang†,
Hongxian Tian‡, Sean Nowlan§, Gedeon Nyengele*, Sajith Mohan Chakkedath*, and Jim Stratigos§
(Invited Paper)
*School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA
†School of Electronics Engineering and Computer Science, Peking University (PKU), Beijing, China ‡School of Electronic and Information Engineering, Beijing Jiaotong University, Beijing, China §Cognosos Inc., 75 5th Street NW, Suite 2190, Atlanta, GA 30308, USA

***Abstract*—We propose a new approach for the uplink in a one-hop multi-gateway wireless packet network. In principle, the proposed technique applies to many types of low-power transmitters, including wireless sensors and RFID tags, both active and passive. Only when requested, each gateway node (or listener) forwards the compressed physical layer samples of packets to a server, which decodes the packets using multiple-input-multiple-output (MIMO) techniques; this functionality could be described as selective application of multi-user MIMO with a distributed receiver array. Packets that have adequate SINR at a gateway are decoded, i.e., captured, and their waveforms are reconstructed and subtracted from stored samples; this subtraction is interference cancellation (IC). After IC, weaker packets may be revealed and decoded by the gateway, enabling successive IC (SIC). The diversity gain of multi-gateway reception provides higher SNR to packets that are not decodable at any gateway, thereby extending range. The spatial multiplexing capability of MIMO enables packets that have too much interference at the gateways to be decoded at the server, thereby supporting energy saving transmit-only strategies. The selectivity or "on demand" feature lowers the fronthaul cost of sending samples to the server. This paper presents preliminary simulation and experimental performance results and overviews the various design concerns of On Demand Network MIMO, such as synchronization, spreading, SIC performance, gateway deployment, and medium access control (MAC).**

***Index Terms*—wireless sensor networks, successive interference cancellation, coordinated multipoint, network MIMO**

I. Introduction

Many Internet of Things (IoT) applications are characterized by low bandwidth, low-power, and low-cost transmitters. These applications often need high reliability and would benefit from range extension. Incumbent technologies such as WiFi, Bluetooth and active RFID are serving a subset of IoT needs but lack the unique combination of features required for longer range applications, especially in outdoor scenarios. The emerging low power wide area (LPWA) network technology is largely the result of a 'clean slate' approach where compatibility with existing standards is not required and instead the various aspects of the physical layer can be optimized to meet the needs of a subset of IoT applications. Multiple-input-multiple-output (MIMO) technology is well known to improve throughput and reliability in wireless networks. While MIMO has seen application in WiFi, Network MIMO, in which multiple remote radio heads or gateway (GW) nodes behave as a large distributed array [1], [2], has not been applied outside of cellular networks, in part because of its expensive fronthaul demands. This paper presents the novel concept of On Demand Network MIMO, which makes Network MIMO affordable for IoT applications by applying it only selectively. Given the drivers of Moore's Law and the increasing availability of software defined radio (SDR) technologies, it is worthwhile to develop such new protocols and enhanced signal processing techniques that could be applied to future LAN and RFID standards to increase their ability to serve a broader range of IoT applications.

The On Demand Network MIMO approach provides reliability and range extension to low-power transmitters by merging two existing technologies: decoding with "capture and SIC" (C&S) [3], [4], [5] at the gateways and decoding with "network MIMO," also known as coordinated multipoint (CoMP) or multi-cell MIMO, in the cloud [1], [2]. "Capture" is the successful decoding of a packet in spite of lower-powered interfering packets. Interference cancellation is the subtracting of the effects of the decoded packet from stored samples of the received signal, thereby making possible the capture of weaker packets. Successive interference cancellation (SIC) is the repeated application of Capture and Interference Cancellation. Network multiple-input-mulitple-output (NMIMO), implemented at a server or data center, utilizes multiple gateway nodes like antennas on a multi-antenna receiver [1].

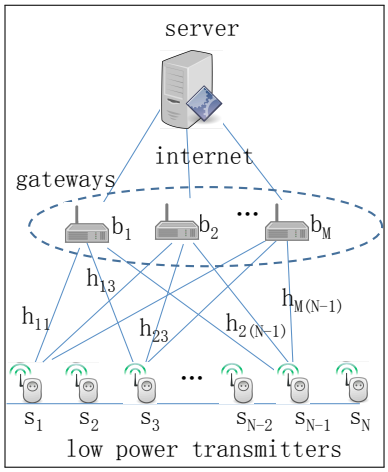


Figure 1. Proposed network architecture.

NMIMO enables network-wide-application of the celebrated MIMO property, which is that when the receiver has at least

*Mary Ann Weitnauer was formerly Mary Ann Ingram.

N antennas, it can decode up to N times more interfering packets, compared to what it can decode with just one antenna, with no net increase in power or bandwidth at the transmitters [6]. However, because the number of bits required to digitize (i.e., sample and quantize) a waveform for NMIMO is higher than the number of bits required to simply forward a decoded packet, the key to the right mix, and the central novelty of the proposed approach, is to apply NMIMO *selectively*, to certain packets that are not decodable at the gateways. C&S at single-antenna receivers dates back to the 1990's [3], [4], but lately, there has been a surge in reported analyses of various types of ALOHA networks that assume C&S functionality [5], [7], [8]. Also, many researchers have recently studied NMIMO, however, to the authors' best knowledge, the combination of C&S and NMIMO, at the gateways and cloud, respectively, has not yet been considered. This paper will present some simulation results that show the high reliability and range extension feature of this combination for the generic network topology of Fig. 1. Experimental results for SIC are shown for a simple packet structure with MSK modulation with spreading and FEC that is similar to active RFID protocols such as 802.15.4[9] and DASH7 (ISO/IEC 18000-7) [10], respectively.

While this paper does not directly address RFID devices that employ modulated backscatter, that is passive and semi-passive tags, the On Demand Network MIMO approach could be applied to them as shown in Figure 2, by extending the *augmented RFID* approach of [11], [12]. The augmented RFID approach separates the two functions of the traditional reader, that of transmission and reception, into physically separate platforms. The transmission function of query and CW is performed by a single high-powered *illuminator*, and the reception function is performed in a distributed fashion by multiple *listeners*. In the topologies considered by [11] and [12], the listeners are deployed rather densely over the field of tags. [12] mentions that soft combining, cancellation, and MIMO is possible, but they do not analyze it. In particular, they do not suggest its selective application. As our results show, the potential benefit of an On Demand NMIMO is a less dense deployment of listeners and higher reliability. If the tag field is small, internet access may not be necessary to convey the samples to the server, however, the On Demand feature may still be desirable to reduce the load on the wired backplane. The advantages of On Demand Network MIMO might also help relax timing and handshaking complexity of collision arbitration protocols such as the slotted ALOHA variant defined in EPC Gen 2 Class 1 [13].

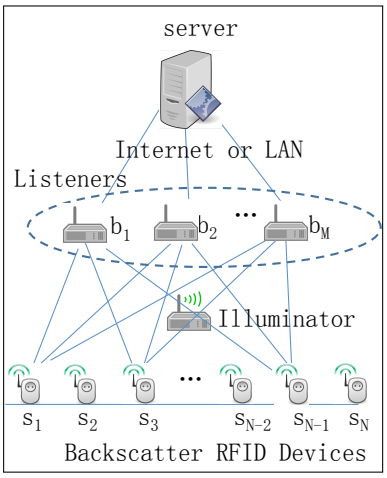


Figure 2. Proposed network architecture.

II. Background and Related Work

A. Physical Layer

1) CRAN: (Centralized, Collaborative, Cloud and Clean Radio Access Network) is a new mobile communications architecture [14], proposed by China Mobile in 2009 and undergoing trials in several countries [15],[16],[14]. In a CRAN, the baseband unit (BBU), which performs the physical layer encoding and decoding and is traditionally housed at the foot of the base station (BS) tower, is moved to a centralized pool or data center, where the baseband processing is done by a virtual BS running on general purpose platform servers [17]. The BSs are replaced by remote radio heads (RRHs), which digitize the uplink signal from the antenna, and then transmit the bits through optical fiber to the data center [18]; the downlink is the reverse process. The term "fronthaul" describes the digitized data on the optical fiber link. In contrast, "backhaul" usually refers to connections between conventional BSs and the central office, which carry no soft samples of signals. Because it is a software-defined network, CRAN can implement any cellular technology. We propose a network that operates like a CRAN for only some packets and with non-fiber transport for the fronthaul, e.g., 4G or WiFi, to support the relatively smaller loads of LPWA networks.

2) Network MIMO: Network MIMO (NMIMO) refers to a large array that is geographically distributed [1], [2], in which the antennas are connected to a central processor by fronthaul links. Application of multiuser MIMO techniques over many cells essentially eliminates interference effects and poor user experience at cell edges and enables the high throughputs from MIMO on a wide-area scale [14]. The early works [19], [20] ignored fronthaul capacity constraints, which have since been identified as a major issue for mobile communication networks, along with delay and timing error on distributed gateways, and much recent effort has been expended on the problem of compression of the RRH signals before they are modulated onto the fronthaul link, e.g.,[21], [22]. We propose NMIMO for packets not decodable by the GWs.

3) SIC: Single-antenna successive interference cancellation (SA-SIC) was originally discussed in the context of DS-CDMA multi-user detection, in which the order of signals for decoding, from strongest to weakest, was shown to be very important [23], [24]. Patel and Holtzman [23] used the de-spreading correlation metric to determine order. Power imbalances [25] and power control [26], [27] are known to enhance SA-SIC. Uncancelled interference is usually modeled as a constant fraction of the signal being cancelled [26] [5]. Multi-antenna SIC, also known as Vertical Bell Labs Layered Space Time (VBLAST), has been demonstrated by many authors [28], [29], [30], where zero-forcing-SIC and MMSE-SIC refer to the type of linear beamforming used in each iteration, before cancellation. Several recent reports of SIC experiments exist [31], [32], [33], including for Zigbee networks [34]. We propose use of single-antenna SIC at the GWs and multi-antenna SIC at the server.

B. Medium Access Control

1) Aloha Methods: Random access (RA) protocols are especially suitable for LPWA applications, characterized by low duty cycle sensors with extended periods of inactivity [35], [36]. The early RA ALOHA protocols [37], [38], [39], [40], assume that if two or more packets arrive in the same slot, both packets are lost. More recent works embrace SIC, assuming that a decoded packet and all its copies can be canceled within single receiver; these include Contention Resolution Diversity Slotted ALOHA (CRDSA) [41], which is implemented in a satellite digital video broadcasting standard [42], and Coded Slotted Aloha (CSA) [43], in which packet copies are transmitted in different slots with different probabilities within a frame. Other authors have considered multiple cooperating receivers [44], [45], [46], which we call "global SIC" in this paper, wherein a packet decoded by a GW can be shared with other GWs, so that they might use it to cancel that packet in their received signals.

For LPWA applications, there is strong motivation to support asynchronous networking, so that the network can include transmit-only (TO) sensor nodes and avoid the overhead required to maintain network synchronization. The Asynchronous Contention Resolution Diversity ALOHA (ACRDA) protocol [47] assumes each transmitter follows a schedule according to its own unsynchronized clock, and each packet has a pointer to any other of its copies in the frame, for the purpose of cancellation. ACRDA assumes no spreading and that the preamble is sized to operate at the minimum SINR for which the payload can be decoded. Using a simulation-based stochastic model for packet interference [48], the authors show ACRDA has less latency and slightly better throughput than CRDSA [47]. We propose a scheme like ACRDA, except we restrict our packet copies to be within a window that is smaller than a frame. To facilitate the On Demand feature, we keep spreading to suppress residual from cancellation as shown by an experiment in Section V, and we do not require pointers within each packet to the locations of other packets.

Researchers [49], [50], [51], [52] and an industry consortium, Weightless SIG [10], consider transmit-only (TO) protocols for LPWA, to avoid the high energy consumption and overhead of bidirectional medium access control (MAC) protocols or to reduce equipment cost. [49] shows TO energy consumption decreased while maintaining the same network coverage, under optimal policies. Huebner et al. [50] demonstrate feasibility using an SDR receiver. For asymmetric networks, which involve disparate rate limitations in uplink vs. downlink, [53] and [54] propose protocols claiming high reliability and energy efficiency. Zhao et al. [51] consider hybrid networks composed of both standard transceivers and TO nodes, and they propose a two-phase constrained-scheduling based MAC protocol, using the "Automatic Resource Estimation (ARE)" method to avoid the collision with the high priority nodes with standard transceivers. We propose a hybrid network of TO radios and "transmit mostly" (TM) transceivers.

III. Network Model

In this section, we specify our assumptions for the MAC and Physical Layers.

A. MAC Layer Model

The sensors will be either transmit only (TO) or "transmit mostly" (TM). TO sensors may or may not have receivers, but if they have them, they never turn them on. Therefore, TO sensors are oblivious to the activities of the GWs and the other nodes. They transmit according to their own clocks, which exhibit drift and random offsets [55]. TM sensors will periodically turn on their receivers and accept feedback or commands from the GWs, but it is our intent that this happens rarely, to save energy. Thus, the TM sensor's clock will also become unsynchronized with the GWs over time. The negative consequences of asynchronization will be compensated by the Network MIMO feature.

In this paper, we assume the GWs are software defined radios (SDRs), to support the varied processing demands at the physical layer, and that they are all synchronized by GPS and have access to the mains power. GPS synchronization provides timing errors less than 0.5 μs [56], which is 1/32nd of our chip period. We note that GWs synchronization is not a necessary assumption; offsets between GWs can be learned over time and compensated, based on packets commonly received. We assume each GW is somehow connected to the internet; our target scenario is that each GW includes a 4G modem supported by a typical multi-phone cellular service contract.

Each sensor selects at random or is assigned a transmission schedule from a known set of schedules, and starts its selected schedule at a random time. We assume that the GWs and/or the server learn the schedule for each sensor through an initialization protocol, can track each sensor's packet arrival times, and can predict when a certain sensor's packet should be received. Thus, the server can know when a certain sensor's packet has been missed, and can request selected GWs to forward physical layer samples corresponding to a missed packet for combining and decoding at the server; this is the "On Demand" feature.

Each schedule is composed of consecutive back-to-back frames. We assume each sensor transmits one new packet per frame. At the beginning of each frame is a "copies window" (CW), when the sensor will send one or more copies of the packet. The first copy is sent at the beginning of the frame, while the other copies are sent at pseudo-random times within the CW. We assume that the random time can be generated by a deterministic pseudo-random generation-algorithm and hence can be a known part of a sensor's schedule. For example, they could be created by a random number generator, using the sensor ID as the random seed.

When a GW first successfully decodes a packet, based on passing a CRC check, it forwards that packet to the server and the other GWs through the internet. No following copies of the packet are forwarded. Each GW stores a certain number of its latest physical layer samples. When a packet has been decoded, its corresponding physical layer samples are synthesized or regenerated and subtracted from the stored samples; this is interference cancellation (IC). In other words, if IC is perfect, after subtraction, the stored samples appear as though the decoded packet had never been transmitted. The

benefit of cancellation is that weaker packets may be revealed and subsequently decoded and forwarded to the server and the other GWs; example experimental results of this will be shown in Section V. Successive application of Capture and IC is called successive interference cancellation (SIC). "Local SIC" happens when a GW cancels a packet that it decoded. "Global SIC" happens when a GW cancels a packet that another GW decoded and forwarded. Global SIC is a form of GW cooperation [45].

We define a time interval, the "SIC space" (SICS), after the last packet copy should have been received, to allow time for local and global SIC to take place and any subsequently decoded packets to be forwarded. If the server is tracking the packet arrival times, or determines that a packet has been missed, then it waits for a SICS before requesting samples of missed packets. If each GW is tracking packet arrival times of sensors from which it often receives packets, or if the GW detects a packet but cannot decode it, then the GW can wait a SICS before proactively sending the samples to the server. Alternatively, the GW can notify the server of a packet detection, but failure to decode. The SICS also defines the minimum samples storage requirement on the GW as SICS sample times the rate.

B. Physical Layer Model

1) Packet Construction: We consider two simplified packet constructions in this paper. In the first construction, we assume the packet has a known preamble followed by an unknown payload. We use the preamble for packet detection, synchronization and channel estimation (DS&CE). For the purposes of this paper, we assume header and control information is part of the payload. We use the first construction in our experimental evaluations of capture and SIC (C&S) at the GWs and maximum ratio combining (MRC) at the server in Section V. In the second construction, we add a post-amble to the end of the first construction, such that the post-amble is the same as the preamble. The post-amble is useful for DS&CE for trailing packets in an offset overlapping packet scenario, when the preamble of the trailing packet is interfered by the leading packet ("offset" means that the interfering packets are not aligned in time, which is the usual case in an asynchronous network). In particular, we use the post-amble for channel estimation for MIMO processing of the overlapped parts of the interfering packets.

In this paper, we introduce the idea of performing DS&CE only at the GWs, even when the payload must be decoded at the server, to support efficient On Demand Network MIMO. The disadvantage of this is that the preamble must be long enough to provide adequate energy for good DS&CE even when the SINR of the payload is insufficient for payload decoding at the GW; this amounts to an increased energy cost for the sensor. There are several advantages, however, of this approach for On Demand Network MIMO. The first advantage is that after the time and frequency offsets of a payload are compensated at the GW, the part of the preamble (and the post-amble if used) that is not interfered by an uncanceled payload can be removed before the physical layer samples are sent to the server for decoding, thereby reducing the fronthaul load. In other words, the preamble does not need to be digitized and sent (i.e., compressed and forwarded) to the server to enable the server to do DS&CE. It may be desirable to signal the estimated DS&CE parameters to the server, particularly if the server is doing the prediction of packet arrival times. Another advantage is that the quality of the DS&CE is better at the GW than at the server, even under high SINR conditions, because of the quantization error and sample rate reduction inherent in compression. A third advantage is that the packet arrival time prediction algorithm, which enables the server or GW to know when a packet has been missed and which is the basis of the On Demand feature, does not need to be so precise. More specifically, when the server requests samples, the endpoints of the time interval of the samples must be specified; there will be error in the estimated endpoints of the interval because of imperfect prediction. However, a long preamble will provide a high peak in the packet detection metric, enabling the GW to make a correct correspondence between the starting endpoint of the samples request interval and the exact location of the start of packet (SOP).

We note that when several SOPs are so close that there could be a correspondence error, then the best policy may be for the sensor to still perform S&CE for each peak of the packet detection metric, and signal those estimates to the server (because they will be better estimates than the server can make for that GW), along with the compressed samples of the interval that contains the union of the entire packets (preamble and payload) of all interfering packets. This condition can be anticipated based on SOP prediction.

2) Modulation, Spreading, and Coding: We consider a transmitter system that combines turbo code forward error correction (FEC) [57], Gold code spreading [58], and minimum shift keying (MSK) modulation [59]. We adopt turbo codes because they are asymmetric, meaning that their simple encoding can be done at sensor nodes with its limited energy whereas the gateway, which is not power limited, can do the complex decoding [60]; the asymmetric approach is a good match to our TO and TM sensors. We adopt the phase spreading sequence (PSS) approach to spread spectrum continuous phase modulation (CPM) [61], [62], [63], in which non-spread bits are mapped to spreading sequences, prior to the CPM modulator, thereby maintaining the bandwidth efficiency of CPM. We selected Gold codes because they have good properties for both autocorrelation and cross-correlation [64]. In this paper, we assume all users employ the same spreading sequence. The payload information bits are Turbo encoded and then spread. The resulting chips are modulated using an MSK modulator. MSK is a constant envelope modulation that enables energy efficient nonlinear power amplifiers [59].

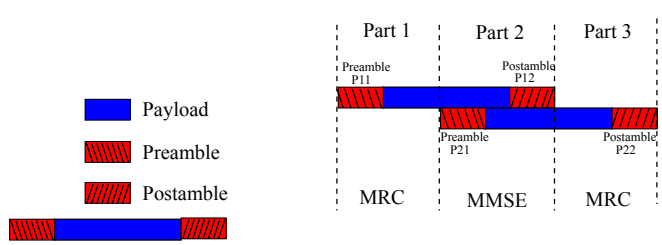
3) Synchronization: Reliable synchronization and channel estimation are very crucial to leverage the benefits from the techniques of SIC, MRC and MIMO under random packet overlapping scenario with unexpected interference. A Data-aided (DA) synchronization algorithm proposed for transmit-only Wireless Sensor Networ (WSN) [65] is adopted to guarantee the accurate phase and frequency offsets estimation as well as effective interference boundary detection. In [65],

we present an interference-insensitive synchronization scheme based on a pseudo noise (PN) preamble, specifically an M-sequence, of arbitrary length. A normalized metric based on double correlation [66] is used to achieve both packet detection and start of packet (SOP) estimation at the same time. A constant false alarm rate (CFAR) detection scheme [67] is adopted to compute the threshold dynamically based on the level of the interference plus noise. The carrier frequency offset (CFO) is estimated based on a received preamble after matched filtering so that it is insensitive to interference as well. After the timing recovering and CFO compensation, the preamble is used as the training sequence for carrier phase offset estimation based on a least-square (LS) estimator with low complexity.

4) Demodulation: Because of the memory in the MSK signal, the optimum detector decides based on the observation of a sequence of received signals. The Viterbi algorithm (VA) is a well known way to implement the maximum-likelihood sequence detector (MLSD) [68]. Rather than the conventional approach which demodulates the chips with the VA prior to despreading, we reduce complexity by combining despreading and demodulation inside the VA. When the spreading is embedded in the demodulation, the branch metric calculation in the VA becomes a many-chips-long correlation of the received signal with the reference modulated spreading sequence, i.e., instead of doing the correlation at the chip level, we can 'zoom out' and perform the correlation at the coded bit level. By choosing only Gold codes with the special property that the number of +1s is always one more than the number of -1s, the structure of the coded bit-rate trellis is the same as the structure of the chip-rate trellis.

C. Network MIMO Modeling

When one considers two packets overlapping at GW as illustrated in Fig.3, the received signal can be divided into three parts. For the best performance, it is optimal to do MRC on Part 1 and Part 3, and MMSE combining on the overlapping part in the middle. The practical challenges are identifying the overlapping part precisely, estimating the channel gains and compensating the CFOs for the two packets correctly. To deal with the practical issues, we design the packet with both preamble and postamble in the same length as illustrated in Fig. 3(a), so that one or the other will be interference-free and can provide optimal synchronization and channel estimation for MIMO processing.



(a) Packet design for the network MIMO with MMSE weights (b) Overlapping scenario at GW

Figure 3. Illustration of MIMO(2×2) signal

For the 2×2 MIMO case, define the channel matrix$H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$, for 2 transmitters and 2 GWs. On GW 1, preamble $P11$ will be used to locate the start of packet (SOP) of the front packet and estimate the channel $\hat{h}_{11}$, while the postamble $P22$ will be used to locate SOP of the early packet and the corresponding channel $\hat{h}_{12}$. Similarly, we will get the channel gain estimates $\hat{h}_{21}$ and $\hat{h}_{22}$ at the GW2.

After synchronization and channel estimation, the MRC scheme to decode the early and late parts of the two streams of data are computed based on the received signal of Part 1 and Part 3 at GW1 and GW2 $y_{1,1}$, $y_{1,3}$, $y_{2,1}$, $y_{2,3}$ are:

$$\hat{x}_1^E = \hat{h}_{11}^* y_{1,1} + \hat{h}_{21}^* y_{2,1} \tag{1}$$

$$\hat{x}_2^L = \hat{h}_{11}^* y_{1,3} + \hat{h}_{21}^* y_{2,3}. \tag{2}$$

Using the estimated channel estimation matrix $\hat{H} = \begin{bmatrix} \hat{h}_{11} & \hat{h}_{12} \\ \hat{h}_{21} & \hat{h}_{22} \end{bmatrix}$, we apply MMSE weights [69] to decode the overlapping part in the middle for the two streams, $\hat{X}^O = [\hat{x}_1^o, \hat{x}_2^o]$, based on the received signal of Part 2 at GWs, $Y^O = [y_{1,2} y_{2,2}]$ as:

$$\hat{X}^O = (\hat{H}^H \hat{H} + NI)^{-1} \hat{H}^H Y^O, \tag{3}$$

where $N = [n_1, n_2]$ are the average noise powers at GW1 and GW2, estimated based on the noise only samples.

Then the two streams of source data are composed as:

$$\begin{aligned} \hat{x}_1 &= [\hat{x}_1^F \ \hat{x}_1^o] \\ \hat{x}_2 &= [\hat{x}_2^o \ \hat{x}_2^B]. \end{aligned} \tag{4}$$

IV. Simulation Results

In this section, we present simulated packet delivery ratios (PDRs) and fronthaul rates for an On Demand NMIMO network. In each deployment trial, we randomly distribute the sensor nodes in a deployment area with a parallelogram shape; an example is shown in Fig.4. The four GW nodes are indicated by the larger red dots. The circles indicate the SISO coverage areas of each GW, if the channels had only path loss. The boundary of the sensor deployment area is tangent to the union of the four GW SISO coverage areas; the tangent aspect ensures that each GW has the same average number of sensors in its coverage area. We define the variable "range ratio" (RR) to be the distance between adjacent GW nodes divided by twice the GW SISO decoding radius. We keep the sensor density constant at about 118 per GW SISO range, but we vary RR in our simulations; smaller RR means more overlap between GW SISO coverage areas and fewer sensors in the deployment area. In Fig.4, RR=0.9.

Each sensor node transmits two copies of a unique packet in each copies window (CW) and the CW is 1/5th of a frame period. The start time of the first frame for each sensor is chosen at random, but thereafter the frames are consecutive. One packet duration is 1/1250th of a frame duration. Each sensor transmits 100 unique packets in the simulation of one deployment trial, and 10 independent deployment trials are simulated. We simulate path loss with exponent 3.2 and independent Rayleigh fading for each sensor-GW channel and

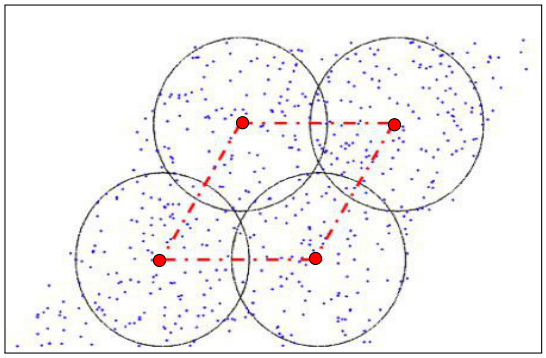


Figure 4. An example of a parallelogram GW deployment. GW decoding range is indicated by the circular arcs. Sensors are distributed randomly within the trapezoid.

for each transmission event (i.e., packet copy). The SINR threshold for decoding in the presence of interfering packets, i.e., the capture threshold, is assumed to be 6 dB [52]. SINR is computed based on average packet power, regardless of degree of partial overlap. In other words, SINR is computed as though the packets had 100% overlap. Average power of residual interference from cancellation is modeled as 0.1 times the average power of the packet that was canceled [5].

For "local SIC," each GW attempts to decode every unique packet. If it decodes one of the copies, it will cancel both copies and and then try to decode more packets. It continues to do SIC until no more packets can be decoded. A packet is considered delivered if at least one GW node is able to decode it. For "global SIC," any unique packet decoded by a GW is shared with the other GWs and they cancel all of its copies. For "MIMO," we consider three cases: two, three, or four GWs forwarding samples for packets not decoded by any GW. For the n-GW NMIMO case, only the n GWs that have the strongest received power for a given packet are commanded to forward the physical layer samples. As we will see, as n increases, the PDR improves but the fronthaul increases by approximately a factor of $n/2$ over the 2-GW NMIMO case.

Even though all sensors' packets and their associated GW and server processing is simulated, we evaluate PDR and fronthaul only for the sensors in the area enclosed by the dashed parallelogram (with a corner at each GW node), in an effort to reduce "edge effects." We define this evaluation area with a parallelogram shape because it can be considered as one tile in a larger network that has a hexagonal pattern of GWs.

The surfaces in Fig.5 indicate the average PDR for each sensor, averaged over the decoding outcomes of 100 unique packet trials for the particular deployment shown in Fig.4, and assuming all four GWs forward samples for any packet destined for NMIMO processing. The colors indicate ranges of PDR, with red indicating PDR> 0.9. "SIC" is what we have called local SIC. "SIC" has C&S at the GW only, $z = 0.1$. "Global SIC," adds GW cooperation. "MIMO" is the result of On Demand NMIMO performed in each slot independently, assuming MMSE processing at the server (assuming all packets decoded by GWs have been cancelled). A packet is declared decoded by NMIMO if the post-MMSE combined SINR of either of its copies is greater than the threshold.

We observe Global SIC is an improvement over SIC, but still leaves a large fraction of sensors with PDR $< 90\%$; we observe the sensors with lower PDR are clustered in the center or "trough" between GWs. In contrast, NMIMO delivers reliability by bringing nearly all PDRs above 90%. This is because NMIMO coherently combines the signals from the different GWs, providing both array and diversity gains.

Figs.6 and 7 give PDR and average fronthaul requirement per unique packet, both as functions of range ratio (RR) and number of GWs selected to forward samples for each packet destined for NMIMO. The PDR is averaged over all the sensors and deployment trials. We observe that increasing the RR causes the PDR to decrease and the fronthaul to increase. We observe in Fig. 6 that there is little improvement offered by 4-GW NMIMO over 3-GW NMIMO.

V. Experiments on Software-defined Radios (SDRs)

To demonstrate On Demand Network MIMO, we tested SIC on GWs, and both MRC and MIMO at the server on USRP SDRs platforms over the air in an indoor environment. For the experiments, we kept the sampling rate constant and let the packet duration vary with respect to the spreading length and coding rate. The system parameters are quantified in Table I.

Table I
System parameters

Payload length, information bit	48
Spreading length,	L
Code rate	R
Sample per chip, S	32
Preamble length, information bit	16
Sampling rate, F_s	$200KHz$
Carrier frequency, F_c	430MHz
Modulation	MSK

1) SIC: Two SDRs transmit different source signals with different repetition rates, and one SDR serves as the GW. Fig.8(a) shows the received over-air signals with spreading length $L = 15$, code rate $R = 1$, and the TX power for two GWs are 0dBm and -5dBm respectively. As we can see, there are two types of overlapping cases. For Case 1, the back of the strong packet is overlapping with the front of the weak packet; while for Case 2 the front of the strong packet is overlapping with the back of the weak packet. The corresponding packet detection result is shown in Fig.8(b) with the peaks indicating the starts of packets (SOPs). The peaks corresponding to strong packets are very sharp and clear, while the peaks corresponding weak packets are relatively lower and are not as distinct as they are when there is no interference. According to the measurements after SIC processing in Figs.8(c) and 8(d), we found the practical residual error is not constant over the packet but tends to initially worsen over time in Fig.8(c). We attribute this phenomenon to phase error that is accumulated in the time domain, as a result of the CFO estimation error. The error is small at the beginning because the channel estimate based on the preamble compensates for

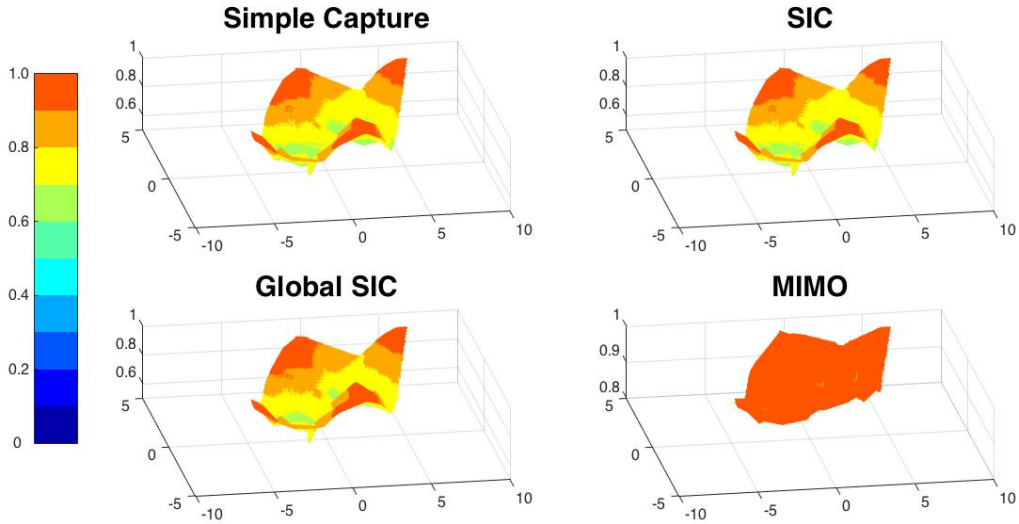


Figure 5. Example of packet delivery ratios (PDRs) for a given deployment of sensors between four gateway nodes, for (a) capture only, (b) C&S at gateways, (c) all of (b) plus decoded packets shared among gateways for further SIC, and (d) all of (c) plus physical layer samples, after all decoded packets cancelled, forwarded to server for MMSE MIMO processing.

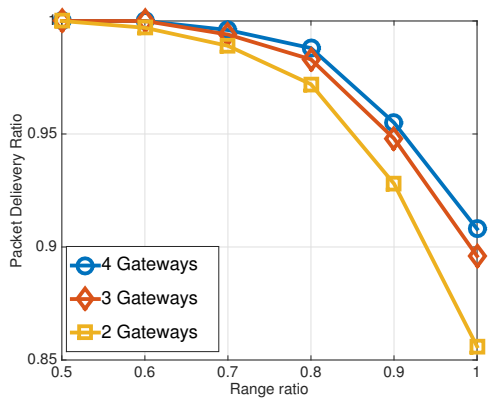


Figure 6. Average PDR.

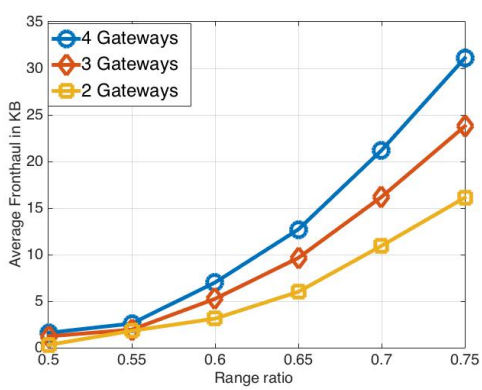
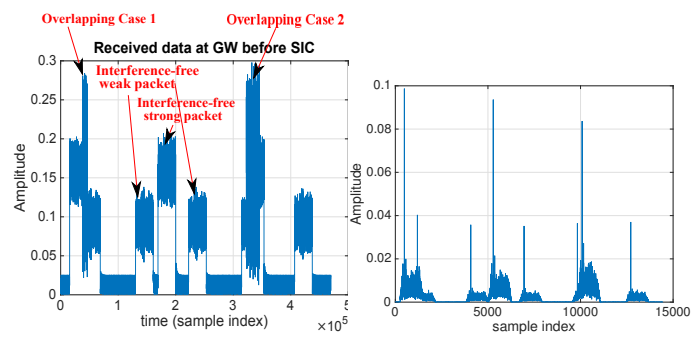
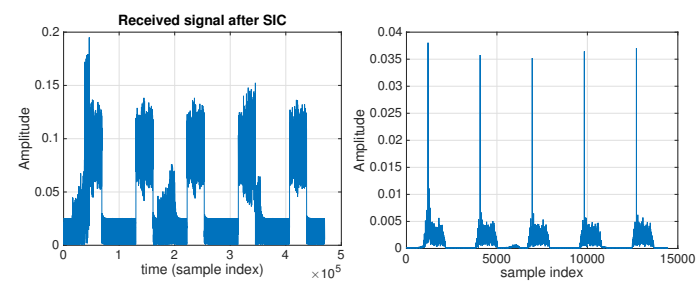


Figure 7. Average fronthaul per unique packet.



(a) Amplitude of received signal before SIC

(b) Amplitude of SOP metric before SIC



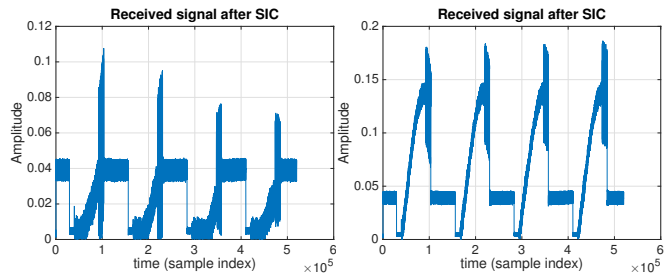
(c) Amplitude of received signal after SIC

(d) Amplitude of SOP metric after SIC

Figure 8. The received signal at GW for SIC processing.

only initial phase offset. As we can see in Fig.8(d), we only see clear peaks indicating the SOPs of weak packets, which demonstrates the effectiveness of the cancellation and ability of the preamble correlation inherent in SOP estimation to suppress the interference from the residual error. Meanwhile, the weak packets are decoded without error after SIC.

According to Fig.9, the shape of the amplitude of realistic



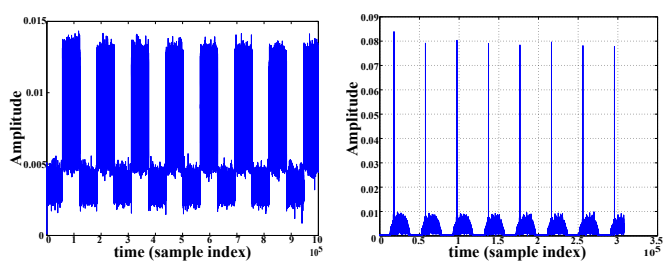
(a) Amplitude of received signal after SIC

(b) Amplitude of received signal after SIC with manually controlled larger CFO error

Figure 9. Residual SIC error (spreading length $L = 31$)

residual SIC error looks like a cosine signal in reality, and when we manually enlarge the CFO error, the phase error grows faster, and the corresponding residual error is larger.

2) Maximum ratio combining (MRC): To improve the performance for the single input and multiple output (SIMO) case, we implement MRC to achieve diversity gain at the server. The experiments are conducted with two SDRs working as GWs, and one SDR working as transmitter.



(a) Amplitude of received signal

(b) Amplitude of SOP metric

Figure 10. The received signal at GW1 (The received signal at GW2 look similar).

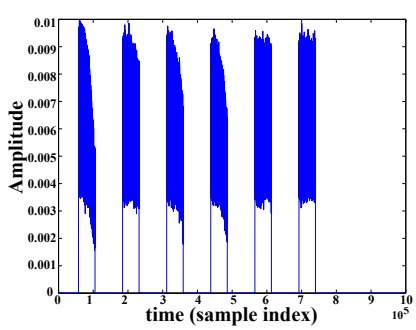


Figure 11. Combined data after MRC at Server.

The received over-air signals at GWs are shown in Fig. 11 with spreading length $L = 31$, code rate $R = 0.5$, TX power$= -15dBm$. The packet detection still works fine under this low SNR as shown in Fig.10(b), and the two streams of weak data are combined at the server to achieve diversity gain based on MRC as shown in Fig.11. The corresponding

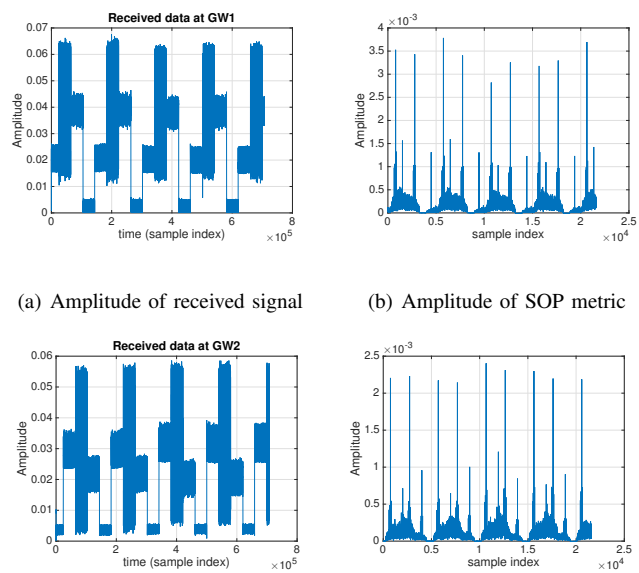
Table II
NUMBER OF ERROR BITS RESULT FOR MRC.

Pkt #	GW1	GW2	Server
1 #	0	1	0
2 #	1	0	0
3 #	0	1	0
4 #	0	2	0
5 #	0	0	0
6 #	1	0	0

decoding performance is shown in Table II with transmitted payload of 48 information bits.

As we can see from Table II, compared to what is achieved at the GWs, MRC improves the decoding performance at the server.

3) Network MIMO Implementation: The MIMO processing includes MRC for non-overlapping parts, and MMSE weights for the overlapping interval to make the most of the MIMO benefits as described in Section III-C. Two gateways are synchronized using reference clock distributor (RCD) board with 1ppm and 10MHz timing and frequency reference, respectively.



(a) Amplitude of received signal

(b) Amplitude of SOP metric

(c) Amplitude of received signal

(d) Amplitude of SOP metric

Figure 12. Received signal at GWs @ Tx power $= -5dBm$.

For the distributed MIMO demonstrations, the over-air signals at GWs are shown in Fig. 12 with spreading length $L = 31$, code rate $R = 1$. According to the corresponding SOPs estimation results in Figs. 12(b) and 12(d), the peaks with relatively larger height, indicating the start of Parts 1 and 3, are clear and reliable for synchronization and channel estimation, as we designed. Therefore, the two streams of source signal $\hat{x}_1, \hat{x}_2$ in Eq. (4) are retrieved and decoded successfully at the server based on the decoding rules in Eq.(4).

VI. Conclusion

In this paper, we present an uplink network MIMO solution to increase the range and reliability of the wireless network composed of low power transmitters, including transmit-only devices, while maintaining moderate fronthaul requirements. Employing local and global successive interference cancellation, the gateways decode and forward most of the packets to the server. Through protocol design, the server makes a timely request for stored physical layer samples from selected gateways for packets that were missed by the gateways. Both simulation and experimental results show a significant improvement in packet delivery ratio when the samples are combined using MIMO techniques at the server. Fronthaul requirements are shown to be reduced through closer spacing of the gateways. According to the experimental results, we found spectrum spreading is still helpful in suppressing the practical residual error from SIC.

Acknowledgment

The authors gratefully acknowledge the partial support of this research by a Phase IIB grant from the Georgia Research Alliance of the State of Georgia.

References

[1] Sivarama Venkatesan, Angel Lozano, and Reinaldo Valenzuela. Network MIMO: Overcoming intercell interference in indoor wireless systems. In *Signals, Systems and Computers, 2007. ACSSC 2007. Conference Record of the Forty-First Asilomar Conference on*, pages 83–87. IEEE, 2007.

[2] David Gesbert, Stephen Hanly, Howard Huang, Shlomo Shamai Shitz, Osvaldo Simeone, and Wei Yu. Multi-cell MIMO cooperative networks: A new look at interference. *Selected Areas in Communications, IEEE Journal on*, 28(9):1380–1408, 2010.

[3] Mahesh K Varanasi and Behnaam Aazhang. Multistage detection in asynchronous code-division multiple-access communications. *Communications, IEEE Transactions on*, 38(4):509–519, 1990.

[4] Alexandra Duel-Hallen. Decorrelating decision-feedback multiuser detector for synchronous code-division multiple-access channel. *Communications, IEEE Transactions on*, 41(2):285–290, 1993.

[5] Andrea Zanella and Michele Zorzi. Theoretical analysis of the capture probability in wireless systems with multiple packet reception capabilities. *Communications, IEEE Transactions on*, 60(4):1058–1071, 2012.

[6] Arogyaswami J Paulraj, Dhananjay Gore, Rohit U Nabar, Helmut Bölcskei, et al. An overview of mimo communications-a key to gigabit wireless. *Proceedings of the IEEE*, 92(2):198–218, 2004.

[7] Dusan Jakovetic, Dragana Bajovic, Dejan Vukobratovic, and Vladimir Crnojevic. Cooperative slotted aloha for multi-base station systems. *Communications, IEEE Transactions on*, 63(4):1443–1456, 2015.

[8] Andrea Munari, Federico Clazzer, and Gianluigi Liva. Multi-receiver aloha systems-a survey and new results. In *Communication Workshop (ICCW), 2015 IEEE International Conference on*, pages 2108–2114. IEEE, 2015.

[9] IEEE 802 Working Group et al. Ieee Standard for Local and Metropolitan Area Networks—Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs). *IEEE Std*, 802:4–2011, 2011.

[10] Weightless SIG. http://www.weightless.org/.

[11] Leonardo Sanchez and Victor Ramos. An epc class-1 generation-2 anti-collision protocol for rfid tag identification in augmented systems. In *RFID Technology (EURFID), 2015 International EURASIP Workshop on*, pages 36–43. IEEE, 2015.

[12] Danilo De Donno, Fabio Ricciato, Luca Catarinucci, Angelo Coluccia, and Luciano Tarricone. Challenge: towards distributed rfid sensing with software-defined radio. In *Proceedings of the sixteenth annual international conference on Mobile computing and networking*, pages 97–104. ACM, 2010.

[13] Jayavardhana Gubbi, Rajkumar Buyya, Slaven Marusic, and Marimuthu Palaniswami. Internet of things (IoT): A vision, architectural elements, and future directions. *Future Generation Computer Systems*, 29(7):1645–1660, 2013.

[14] I Chih-Lin, Jinri Huang, Ran Duan, Chunfeng Cui, Jesse Xiaogen Jiang, and Lei Li. Recent progress on C-RAN centralization and cloudification. *Access, IEEE*, 2:1030–1039, 2014.

[15] K Chen and R Duan. C-RAN–the road towards green RAN. *whitepaper of China Mobile Research Institute*, 2011.

[16] I Chih-Lin, Corbett Rowell, Shuangfeng Han, Zhikun Xu, Gang Li, and Zhengang Pan. Toward green and soft: a 5G perspective. *Communications Magazine, IEEE*, 52(2):66–73, 2014.

[17] Jingchu Liu, Sheng Zhou, Jie Gong, Zhisheng Niu, and Shugong Xu. On the statistical multiplexing gain of virtual base station pools. In *Global Communications Conference (GLOBECOM), 2014 IEEE*, pages 2283–2288. IEEE, 2014.

[18] Philippe Chanclou, Anna Pizzinat, Fabien Le Clech, To-Linh Reedeker, Yannick Lagadec, Fabienne Saliou, Bertrand Le Guyader, Laurent Guillo, Qian Deniel, Stéphane Gosselin, et al. Optical fiber solution for mobile fronthaul to achieve cloud radio access network. In *Future Network and Mobile Summit (FutureNetworkSummit), 2013*, pages 1–11. IEEE, 2013.

[19] Aaron D Wyner. Shannon-theoretic approach to a gaussian cellular multiple-access channel. *Information Theory, IEEE Transactions on*, 40(6):1713–1727, 1994.

[20] Oren Somekh and Shlomo Shamai. Shannon-theoretic approach to a gaussian cellular multiple-access channel with fading. *Information Theory, IEEE Transactions on*, 46(4):1401–1425, 2000.

[21] Lei Zhou and Wei Yu. Uplink multicell processing with limited backhaul via per-base-station successive interference cancellation. *Selected Areas in Communications, IEEE Journal on*, 31(10):1981–1993, 2013.

[22] Mugen Peng, Chonggang Wang, Vincent Lau, and H Vincent Poor. Fronthaul-constrained cloud radio access networks: insights and challenges. *Wireless Communications, IEEE*, 22(2):152–160, 2015.

[23] Pulin Patel and Jack Holtzman. Analysis of a simple successive interference cancellation scheme in a DS/CDMA system. *Selected Areas in Communications, IEEE Journal on*, 12(5):796–807, 1994.

[24] Sergio Verdu. *Multiuser detection*. Cambridge university press, 1998.

[25] Riccardo De Gaudenzi and Oscar DelRío Herrero. Advances in random access protocols for satellite networks. In *Satellite and Space Communications, 2009. IWSSC 2009. International Workshop on*, pages 331–336. IEEE, 2009.

[26] Jeffrey G Andrews and Teresa H Meng. Optimum power control for successive interference cancellation with imperfect channel estimation. *Wireless Communications, IEEE Transactions on*, 2(2):375–383, 2003.

[27] Florian Collard and Riccardo De Gaudenzi. On the optimum packet power distribution for spread aloha packet detectors with iterative successive interference cancelation. *Wireless Communications, IEEE Transactions on*, 13(12):6783–6794, 2014.

[28] Peter W Wolniansky, Gerard J Foschini, GD Golden, R Valenzuela, et al. V-BLAST: An architecture for realizing very high data rates over the rich-scattering wireless channel. In *Signals, Systems, and Electronics, 1998. ISSSE 98. 1998 URSI International Symposium on*, pages 295–300. IEEE, 1998.

[29] GD Golden, CJ Foschini, Reinaldo A Valenzuela, and PW Wolniansky. Detection algorithm and initial laboratory results using V-BLAST space-time communication architecture. *Electronics letters*, 35(1):14–16, 1999.

[30] Thomas Haustein, Andreas Forck, Holger Gäbler, Volker Jungnickel, and Stefan Schiffermüller. Real-time signal processing for multiantenna systems: algorithms, optimization, and implementation on an experimental test-bed. *EURASIP Journal on Applied Signal Processing*, 2006:136–136, 2006.

[31] Yubo Yan, Panlong Yang, Xiang-Yang Li, Yafei Zhang, Jianjiang Lu, Lizhao You, Jiliang Wang, Jinsong Han, and Yan Xiong. Wizbee: Wise zigbee coexistence via interference cancellation with single antenna. *Mobile Computing, IEEE Transactions on*, 14(12):2590–2603, 2015.

[32] Michael Grieger, Patrick Marsch, and Gerhard Fettweis. Uplink base station cooperation by iterative distributed interference subtraction. In *Personal, Indoor and Mobile Radio Communications, 2009 IEEE 20th International Symposium on*, pages 1973–1977. IEEE, 2009.

[33] Daniel Halperin, Thomas Anderson, and David Wetherall. Taking the sting out of carrier sense: interference cancellation for wireless lans. In *Proceedings of the 14th ACM international conference on Mobile computing and networking*, pages 339–350. ACM, 2008.

[34] Linghe Kong and Xue Liu. mzig: Enabling multi-packet reception in zigbee. In *Proceedings of the 21st Annual International Conference on Mobile Computing and Networking*, pages 552–565. ACM, 2015.

[35] Xiong Xiong, Kan Zheng, Rongtao Xu, Wei Xiang, and Periklis Chatzimisios. Low power wide area machine-to-machine networks: key techniques and prototype. *Communications Magazine, IEEE*, 53(9):64–71, 2015.

[36] Oscar del Rio Herrero and Riccardo De Gaudenzi. Generalized analytical framework for the performance assessment of slotted random access protocols. *Wireless Communications, IEEE Transactions on*, 13(2):809–821, 2014.

[37] Norman Abramson. The ALOHA system: another alternative for computer communications. In *Proceedings of the November 17-19, 1970, fall joint computer conference*, pages 281–285. ACM, 1970.

[38] Lawrence G Roberts. ALOHA packet system with and without slots and capture. *ACM SIGCOMM Computer Communication Review*, 5(2):28–42, 1975.

[39] Hiromi Okada, Y Igarashi, and Y Nakanishi. Analysis and application of framed ALOHA channel in satellite packet switching networks-FADRA method. *Electronics Communications of Japan*, 60:72–80, 1977.

[40] Gagan L Choudhury and Stephen S Rappaport. Diversity ALOHA-a random access scheme for satellite communications. *Communications, IEEE Transactions on*, 31(3):450–457, 1983.

[41] Enrico Casini, Riccardo De Gaudenzi, and Od R Herrero. Contention resolution diversity slotted ALOHA (CRDSA): An enhanced random access schemefor satellite access packet networks. *Wireless Communications, IEEE Transactions on*, 6(4):1408–1419, 2007.

[42] DVB Second Generation. Digital video broadcasting (dvb); second generation DVB interactive satellite system; part 2: Lower layers for satellite standard. *ETSI EN Std*, 301 545-2 V1.1.1, Jan. 2012.

[43] Gianluigi Liva. Graph-based analysis and optimization of contention resolution diversity slotted ALOHA. *Communications, IEEE Transactions on*, 59(2):477–487, 2011.

[44] Andrea Munari, Federico Clazzer, and Gianluigi Liva. Multi-receiver aloha systems–a survey and new results.

[45] Dusan Jakovetic, Dragana Bajovic, Dejan Vukobratovic, and Vladimir Crnojevic. Cooperative slotted ALOHA for multi-base station systems. *Communications, IEEE Transactions on*, 63(4):1443–1456, 2015.

[46] Shyamnath Gollakota, Samuel David Perli, and Dina Katabi. Interference alignment and cancellation. In *ACM SIGCOMM Computer Communication Review*, volume 39, pages 159–170. ACM, 2009.

[47] Riccardo De Gaudenzi, Oscar del Rio Herrero, Gunes Acar, and Eloi Garrido Barrabes. Asynchronous contention resolution diversity ALOHA: Making CRDSA truly asynchronous. *Wireless Communications, IEEE Transactions on*, 13(11):6193–6206, 2014.

[48] E Casini and etc. Method of packet mode digital communication over a transmission channel shared by a plurality of users. U.S. Patent 8 094 672 B2, 2012.

[49] Bartlomiej Blaszczyszyn and Bozidar Radunovic. Using transmit-only sensors to reduce deployment cost of wireless sensor networks. In *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*. IEEE, 2008.

[50] Christof Huebner, Rachel Cardell-Oliver, Stefan Hanelt, Tino Wagenknecht, and Alvaro Monsalve. Long-range wireless sensor networks with transmit-only nodes and software-defined receivers. *Wireless Communications and Mobile Computing*, 13(17):1499–1510, 2013.

[51] Jia Zhao, Chunming Qiao, Raghuram S Sudhaakar, and Seokhoon Yoon. Improve efficiency and reliability in single-hop wsns with transmit-only nodes. *Parallel and Distributed Systems, IEEE Transactions on*, 24(3):520–534, 2013.

[52] Bernhard Firner. *Transmit only for dense wireless networks*. PhD thesis, Rutgers University-Graduate School-New Brunswick, 2014.

[53] Raghuram S Sudhaakar, Chunming Qiao, Seokhoon Yoon, and Jia Zhao. A MAC protocol for real-time sensing applications using asymmetric transceivers. In *Mobile Adhoc and Sensor Systems, 2009. MASS'09. IEEE 6th International Conference on*, pages 150–159. IEEE, 2009.

[54] Ren P Liu, Zvi Rosberg, Lain B Collings, Carol Wilson, Alex Y Dong, and Sanjay Jha. Overcoming radio link asymmetry in wireless sensor networks. In *Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008. IEEE 19th International Symposium on*, pages 1–5. IEEE, 2008.

[55] Atanu Guchhait and RM Karthik. Joint minimum variance unbiased and maximum likelihood estimation of clock offset and skew in one-way packet transmission. In *Vehicular Technology Conference (VTC Spring), 2015 IEEE 81st*, pages 1–6. IEEE, 2015.

[56] Zan Li, Desislava C Dimitrova, Torsten Braun, and Denis Rosário. Highly accurate evaluation of gps synchronization for tdoa localization. In *Wireless Days (WD), 2013 IFIP*, pages 1–3. IEEE, 2013.

[57] Claude Berrou and Alain Glavieux. Near optimum error correcting coding and decoding: Turbo-codes. *Communications, IEEE Transactions on*, 44(10):1261–1271, 1996.

[58] Esmael H Dinan and Bijan Jabbari. Spreading codes for direct sequence cdma and wideband cdma cellular networks. *Communications Magazine, IEEE*, 36(9):48–54, 1998.

[59] Subbarayan Pasupathy. Minimum shift keying: A spectrally efficient modulation. *IEEE Communications Magazine*, 17(4):14–22, 1979.

[60] Liang Li, Robert G Maunder, Bashir M Al-Hashimi, and Lajos Hanzo. A low-complexity turbo decoder architecture for energy-efficient wireless sensor networks. *Very Large Scale Integration (VLSI) Systems, IEEE Transactions on*, 21(1):14–22, 2013.

[61] William D Lane and Aubrey M Bush. Spread-spectrum multi-h modulation. *Selected Areas in Communications, IEEE Journal on*, 8(5):728–742, 1990.

[62] Tat M Lok and James S Lehnert. Ds/ssma communication system with trellis coding and cpm. *Selected Areas in Communications, IEEE Journal on*, 12(4):716–722, 1994.

[63] Fengfang Yang, SH Leung, CY Ngan, and Guangguo Bi. The performance and design criterion of phase spreading sequences for ds/ssma communications with full response cpm over rayleigh fading channels. In *Global Telecommunications Conference, 1999. GLOBECOM'99*, volume 1, pages 914–918. IEEE, 1999.

[64] Dilip V Sarwate and Michael B Pursley. Crosscorrelation properties of pseudorandom and related sequences. *Proceedings of the IEEE*, 68(5):593–619, 1980.

[65] Qiongjie Lin and Mary Ann Weitnauer. Interference-insensitive synchronization scheme of MSK for transmit-only wireless sensor networks. In *ICC'16- Wireless Communications Symposium, IEEE International Conference on Communications*, 2016.

[66] Zae Yong Choi and Yong H Lee. Frame synchronization in the presence of frequency offset. *Communications, IEEE Transactions on*, 50(7):1062–1065, 2002.

[67] LL Scharf Addison. *Statistical signal processing: detection, estimation and time series analysis*. Addison-Wesley, 1991.

[68] John G Proakis. Digital communications. 1995. *McGraw-Hill, New York*.

[69] Ping Li, Debashis Paul, Ravi Narasimhan, and John Cioffi. On the distribution of sinr for the mmse mimo receiver and performance analysis. *Information Theory, IEEE Transactions on*, 52(1):271–286, 2006.