Demonstration of a New Degree of Freedom in Wireless Routing: Concurrent Cooperative Transmission

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Abstract

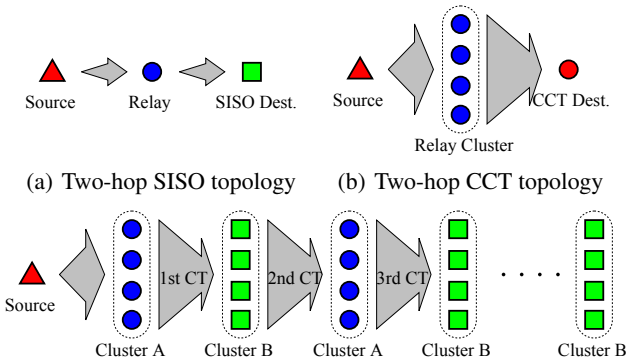
Cluster transmission, also called Concurrent Cooperative Transmission (CCT) in this paper, enables a collection of power-constrained embedded sensors to transmit as a group and achieve a transmit range that is much greater than the range of a single device. CCT brings a new flexibility to the network layer; for example, CT can be used for load balancing or for overcoming a partition. CCT is also the basis for a fast, contention-free method of broadcasting. A method for achieving cluster transmit time synchronization is described for the non-coherent FSK type of modulation. In this method, nodes derive their synchronization from a received packet. Experimental results are presented for an indoor office environment at 2.4 GHz. Root mean squared (rms) transmit time spreads are reported for a two-hop network as well as for a "ping pong" experiment, which has ten consecutive CCT hops. Examples of CCT range extension are also presented.

Keywords

Wireless communication, Wireless networks, Cooperative Transmission, Software Defined Radio

1 Introduction

To stay within cost and size constraints, wireless embedded sensors typically have limited transmission range. Also, to reduce cost, the number of Sinks or Gateway nodes may be limited, implying that multi-hop networking may be needed to reach a Sink. Depleted energy stores and dynamic propagation environments may occasionally break communication links, inducing partitions in the network. Cooperative transmission (CT) is a physical layer communication scheme that can help relieve these energy depletion and partition problems. CT enables a collection of spatially separated sensor nodes to collaborate in their transmission of the same source message to give a 10 dB to 20 dB boost in the received signal-to-noise ratio (SNR) [12]. The SNR boost comes from the independence of the fading channels between the receiver and each cooperator and from the simple adding or pooling of transmit powers of the cooperating nodes; these gains are realized through physical layer combining. When this SNR advantage is used to extend range, the network layer can benefit in terms of faster broadcasts (contention-free and fewer hops), improved energy balance (by hopping over "bottleneck" nodes to preserve their energy), enhanced path diversity, and elimination of partitions.



(a) Two-hop SISO topology (b) Two-hop CCT topology

(c) Multiple hops CCT topology

Figure 1. The network topologies used in the experiments

While CT has been studied vigorously in the wireless communications community for the last seven years, there have been very few physical demonstrations and an understandable skepticsm of CT in the networking community. This paper presents new experimental results showing the practicality of CT for range extension in an indoor office building, for radios that do energy efficient FSK transmission and non-coherent reception at 2.4 GHz. In particular, this paper explains a simple method for time-synchronizing the transmissions of nodes doing CT, and shows that this synchronization is stable for successive CT hops, a necessary property for CT-based broadcasting. The paper also gives some example two-hop ranges of CT and non-CT, showing evidence of CT range extension with real devices.

There are three types of CT: coherent beamforming, Time-Division CT (TDCT), and "Concurrent CT" (CCT). While high-performing, coherent beamforming requires detailed channel information at the transmitters, and therefore

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has the highest network overhead [13]. In TDCT, cooperating nodes transmit in non-overlapping time intervals [11], which makes this approach unattractive for range extension. In CCT, all the cooperating nodes transmit nearly simultaneously, through a small number of diversity channels, which are orthogonal channels that fade independently. For example, diversity channels can be created using orthogonal carrier frequencies (as in this paper), or by using distributed space-time block code (STBC) [12].

In ideal CCT, the differences in the nodes' transmit times are negligible compared to the multipath delay spread of the channel, so that a receiver cannot distinguish a CCT signal from a transmission from a single radio platform that has an array antenna. In this paper we show statistics for the transmit time spreads for two different topologies of the cooperating nodes.

Our motivations are two-fold. First, we wish to prototype a suite of broadcasting and unicasting protocols that we developed [17] [8] [16], based on the opportunistic large array [15]. The OLA is a totally decentralized type of CCT where the number of cooperators in a hop cannot generally be predicted; rather they are the nodes that can decode the message and which have not previously relayed the message. The concept was also independently developed as the Barrage Relay Network [2]. These OLA-based schemes have the advantage of fast, energy efficient, contention-free broadcasts [15] [8], and unicasts that are robust to node loss and mobility [16] [2].

The other motivation has been to use CT range extension as an energy balancing tool in multi-hop wireless sensor networks (WSNs) [7]. In such networks, the nodes surrounding the Sink node tend to deplete their batteries first because they must relay the packets from the rest of the network. [7] shows that by occasionally and pre-emptively tapping some of the would-be trapped energy in the disconnected nodes, the nodes near the Sink can be relieved of some of their relaying burden, thereby increasing network life dramatically.

Of the reports on CT implementation, most are for TDCT [3] [10] [14]. A demonstration of CCT-based broadcasting is claimed in [4], but few details are given. The same type of CCT described in the present paper was explained in more detail by the authors in [5]. [5] also included synchronization performance for a two-hop topology that is similar to this paper, but in [5] the topology is confined to one room, whereas in this paper, it is spread over a much wider area, so that path loss and shadowing play more of a role.

The remainder of this paper is organized as follows. The related work is discussed in Section II. In Section III the cluster transmit time synchronization method is proposed and experimental setup is addressed in Section IV. Finally, the measured results achieved with the proposed methods are presented in Section V.

2 Cluster Transmit Time Synchronization

Our approach uses a recently received packet as the time reference for the next transmission. The received packet can be the data packet from the previous-hop transmitter or a previous-hop CCT cluster. The method reported here does not attempt to compensate for different propagation distances between the cooperators and the previous hop transmitter(s). Instead, we rely on the natural proximity of dominant cooperators, which follows from their being both (i) within range of the previous hop transmission and (ii) nearest to the receiving node. The starting time of the received packet can be estimated by cross-correlating the received signal with a known preamble or by cross-correlating two consecutive preambles. In general, packet timing can be estimated by finding a threshold or peak of the correlation output [9]. We explain our approach in more detail in the next section.

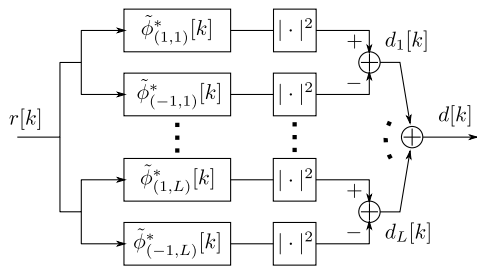


Figure 2. Non-coherent BFSK demodulator with equal gain combining of orthogonal frequency diversity

Our idea is that the cooperating transmitters start their transmissions at the same time. However, if individual cooperators are allowed to transmit as soon as they are ready, hardware disparities, fading channels, differences in propagation distances, differences in processing times, and noise cause transmit time variations of 4 ms to 30 ms [5]. Therefore, in our method, the cooperating nodes wait to transmit for a fixed period T_{proc} after receipt of the synch packet. T_{proc} is selected so that at least $\alpha \times 100\%$ of the cooperators will be ready to transmit when T_{proc} expires, where α is a design parameter such that $0 \leq \alpha \leq 1$.

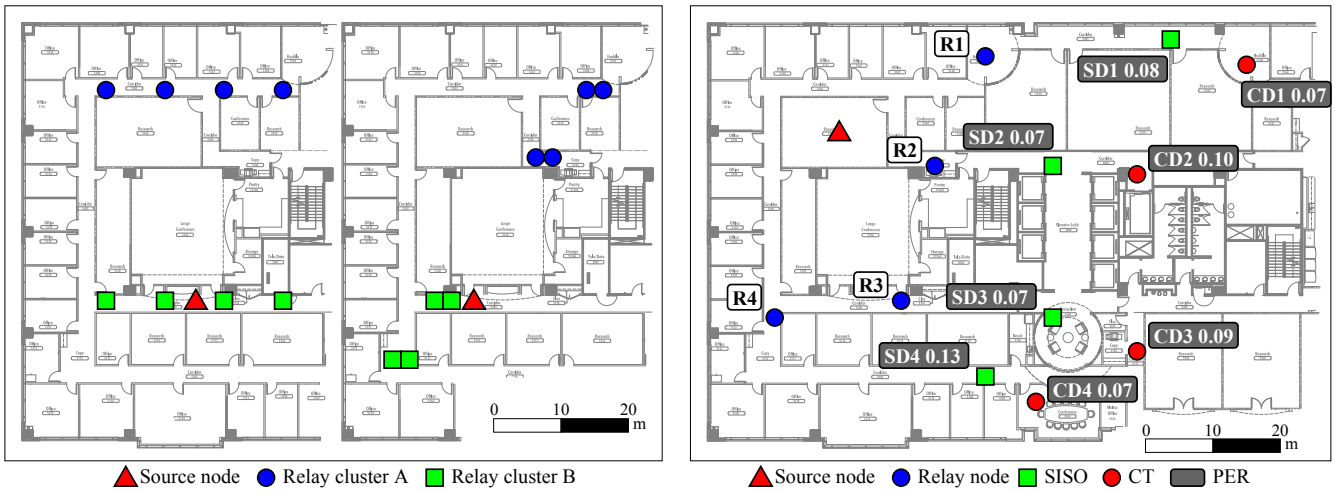
Because different relays have different clocks, nodes with fast clocks will have T_{proc} expiring before the nodes with slow clocks. Therefore differences in the clock rates must be compensated, so the cooperators will fire (i.e. relay) at the same time. Our solution for this is that the original source encodes the length in samples of each packet in a two-byte field in the header. The ith relay node counts how many non-zero samples it used when it received the packet, and divides the reference length by this number to get a ratio, γ_i. For example, if the clock is fast, $\gamma_i > 1$. To compensate the clock rate, T_{proc} is simply replaced by $\gamma_i T_{proc}$.

2.1 Start of Packet Detection

Let us assume for simplicity of notation that the packet contains only the preamble. We create diversity channels using orthogonal frequencies. The baseband signal of BFSK in the l_{th} orthogonal channel with frequency separation $\triangle f$ is as follows:

$$s_l(t) = \sqrt{\frac{2\mathcal{E}}{T}} e^{j\pi\{(p[m](1/2)+l)\triangle f\}t} \text{ for } mT \leq t < (m+1)T$$

where $p[m]$ denotes the preamble sequence $\in \{-1,1\}$ for $0 \leq m < M-1$ and $\mathcal{E}$ is transmit symbol energy. The received signal superimposing L orthogonal transmissions



(a) Two topologies for "ping pong" experiment

(b) The floor plan for range extension experiment and results

Figure 3. The floor map of the experiments which had conducted on the fifth floor of Centergy Building in Georgia Institute of Technology

through complex flat fading channel gains h_l and propagation delays τ_l, $1 \leq l \leq L$, is given by

$$r(t) = \sum_{l=1}^{L} h_l s_l(t-\tau_l) e^{-j2\pi\varepsilon_l t} + w(t) \tag{1}$$

where $w(t)$ is complex white Gaussian noise with variance N. At the receiver, the digitized $r(t)$ passes through L pairs of BFSK envelope detectors which consist of matched filter banks and squarers as shown in Fig. 2. At the high SNR approximation, the discrete time representation of the output of l_{th} diversity channel is given by

$$d_l[k] = \left|r[k] * \tilde{\phi}^*_{(1,l)}[k]\right|^2 - \left|r[k] * \tilde{\phi}^*_{(-1,l)}[k]\right|^2 \tag{2}$$

and the outputs are are combined to produce the bipolar, soft-valued sequence $d[k] = \sum_{l=1}^{L} d_l[k]$ which is an equal gain combining for non-coherent demodulation. The output of a preamble correlator is $\Omega[k] = \sum_s d[s] p\left[\lfloor (s-k)/S \rfloor\right]$ where S is the number of samples per symbol. It is noted that the timing accuracy of threshold or peak detection of correlation output depends on the rising time of $\Omega[k]$. In order to avoid the accuracy degradation caused by CFO, we estimate SOR as

$$\hat{\xi} = \frac{\sum n \Omega_w[n]}{\sum \Omega_w[n]} \tag{3}$$

where $\Omega_w[k]$ is the windowed correlator output which is opened only for one symbol bin.

3 Experimental Results

Each wireless node in these experiments is composed of a Daughterboard (RF front end), an Universal Software Radio Peripheral (USRP1) board, a personal computer (PC), and the GNU radio software. The USRP1 board has an ADC/DAC and a FPGA to convert passband signal to baseband signal and vice versa. All baseband processing is done on the PC. Since, at the time of writing, a time-management method in GNURadio so called *in-band signaling* was under-development, we modified FPGA code of a USRP1 and GNURadio software to support time-management. We also designed to generate an external trigger output at the time of transmission, which is connected physically by wire to a customized FPGA board that we call an observer device. We emphasize that the observer device, which receives trigger signals from transmitters by wire to calculate RTTS, provides no synchronization to the relays.

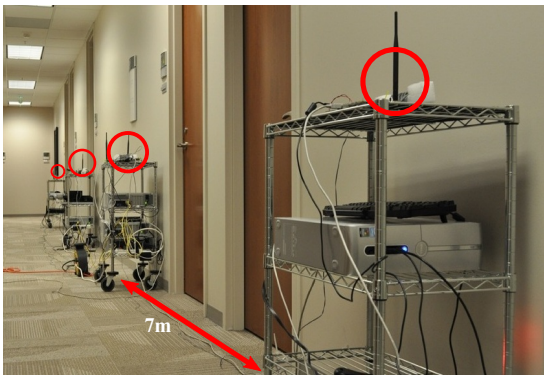
Binary frequency shift keying (BFSK) with non-coherent envelope detection was used for the experiments. Cooperative transmit diversity was achieved by choosing orthogonal center frequencies. We used 64 kbps bit-rate with 1 Mhz sampling-rate. The total length of a packet is 24 bytes consisting of 4 bytes preamble, 6 bytes header, 10 bytes data and 2 bytes CRC. The packet is scrambled at every transmission in which the index of scrambler is included in the header. All baseband processing for non-coherent BFSK modulator/demodulator and the packet detection scheme discussed in the previous section are written in the C++ and Python languages.

3.1 Time Synchronization Experiment

This experiment focuses on measuring transmission time spread of cooperative nodes in the multiple-hop CCT topology in Fig. 1(c). The rms transmit time spread (RTTS) of cooperative relay nodes in l_{th} CT can be calculated by

$$\sigma^l_\tau = \sqrt{\frac{\sum_i^N (t^l_{T,i} - \hat{t}^l_T)^2}{N-1}} \tag{4}$$

where $t^l_{T,i}$ is a measured transmission time of i_{th} relay node in l_{th} CT and $\hat{t}^l_T$ is the sample mean of transmission time of all relay nodes. As shown in Fig. 1(c) two groups of cooperative nodes transmit the source message back and forth up to 10 hops (or "CT"s). The experiment was repeated 500 times to get 500 trials of σ^l_τ, which is collected by the observer de-



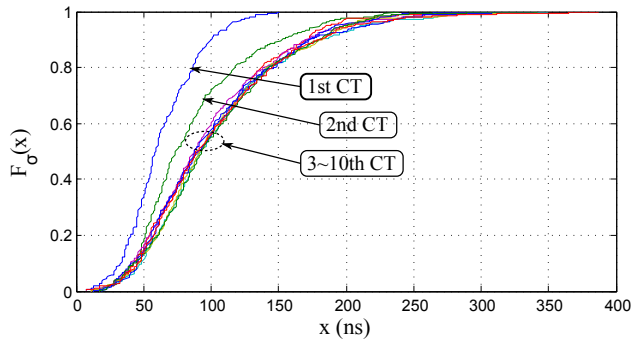
(a)

(b)

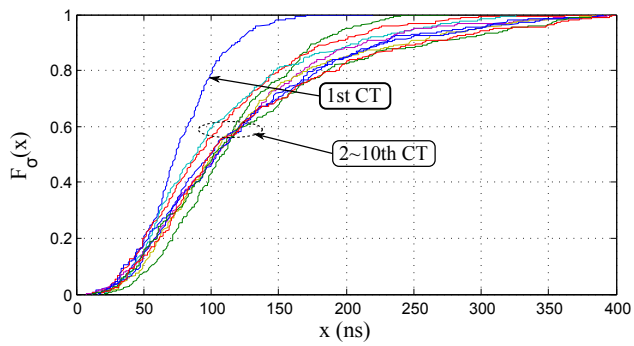
Figure 4. Photographs of (a) one of the linear clusters in the "ping pong" experiment, and (b) the destination cart for the range extension experiment.

vices at each CT. We considered two different cluster topologies, as shown in Fig. 3(a); the left topology features parallel linear clusters, which might approximate broadcast OLAs in a strip network. A photograph of one of the linear clusters is shown in Fig. 4(a). The right topology in Fig. 3(a) is intended to be a worst case topology in terms of propagation delay differences [1].

Fig. 5 shows the empirical RTTS of cooperative nodes in the two topologies. Each curve represents an empirical cumulative density function (CDF) of RTTS of each CT. We observe that the RTTS of the first CT provides better performance than other CTs in both topologies. This is because the timing reference of cooperative nodes in 1_{st} CT is a single source transmission in which there is no timing spread caused by multiple timing offsets from previous cluster. We also observe that the CDFs of RTTS of CTs 3 through 10 essentially overlay each other, which implies the practicality of concurrent multi-hop CT. Moreover 90% of RTTS is less than 300ns in both topologies, which indicates that concurrent CT can support up to 300 kbps data rate in narrowband waveforms without ISI degradation [6]. Broadband waveforms such as OFDM with an 0.8*us* guard interval could also be supported.



(a) RTTS in the first topology



(b) RTTS in the second topology

Figure 5. Measured RTTS of "ping pong" experiment

3.2 Range Extension Experiment

Our aim in this experiment is to compare the two-hop range of conventional Single Input Single Output (SISO) multi-hop with the two-hop range of 4-element CCT, corresponding to topologies (a) and (b), respectively, in Fig. 1. We define "range" to be the maximum distance between the relays and the destination, such that the packet error rate (PER), when the effects of multipath fading are averaged out, is approximately ten percent (0.1). For the CCT cluster, we consider a "maximally dispersed" topology, which means that each cluster node is as far as possible from the source as well as being well separated from the other cluster nodes, while keeping an average PER of approximately 0.01. Fig. 3(b) indicates, on the floor plan of the building, the source, relay and destination locations corresponding to the two-hop topologies of Fig. 1(a) and 1(b), using the same symbols. For each SISO destination, the previous-hop node is the nearest relay. For example, for SD2, the associated relay is R2. The CCT destinations are CD1-CD4, and they receive the CCT signal from all four relays.

For each destination and for each multipath realization, the PER at the destination is calculated based on 1000 transmitted packets. Next, the PER is averaged over 120 independent multipath channel realizations created by moving the terminals around in a local area, so that the shadowing effects are preserved and a 90% confidence interval of about 0.06 is achieved. 15 independent channel realizations are obtained by having 15 different GNU radios simultaneously receive the signal at the destination, as shown in Fig. 4(b).

For the CCT range measurement, moving the *relays* to eight different locations in a local area generates $8 \times 15 = 120$ different multipath channel realizations. For each SISO range measurement, we placed a small cart at the relay location; the cart held 4 GNU radios. A measurement was made for each radio on the cart, resulting in $4 \times 15 = 60$ channel realizations. Moving the small cart once created another 60 realizations for a total of 120.

We observe that the CCT destinations are further to the right than the SISO destinations, indicating range extension. However, the range extension appears to be only about 80%, which is less than the predicted factors of 2 to 4. The shortfall can be explained in part by the non-homogeneity of the channels and the limitations of where we could put the measurement carts. For example, the top three SISO destinations are all within line-of-sight (LOS) or near LOS of one of the relays, while the CCT destinations are all non-LOS (NLOS). LOS gives a strong advantage over NLOS, especially in the center of the building where the cement walls surrounding the elevators and stairwells strongly attenuate the signal. Another factor contributing to the shortfall is the large distance between relays, which implied that, for any particular CCT destination, at most only two relays made significant contributions to the total power (these results could not be shown because of space constraints), so there was effectively only second order diversity from two relays. Therefore, we think that more range extension would be observed from (i) a denser distribution of relays, (ii) placing the SISO destinations also in NLOS locations, and (iii) performing the experiment in a part of the building away from the cement core.

4 Conclusion

In this paper, we have demonstrated Concurrent Cooperative Transmission (CCT) by using SDRs and also presented experimental transmit time synchronization and range extension results in a typical indoor environment. This demonstration may be useful in considering CT-based medium access control and network layer protocols, which bring flexibilities to balance energy consumption over a network or overcome a partition. Our experiments show that CCT is practical for indoor environments. Our ongoing work includes exploration of CCT-based network layer protocols [17] [16] [7] and more spectrally efficient modulation schemes using this testbed.

5 References

[1] R. Bhatia and C. Davis. A better bound on the variance. *The American Mathematical Monthly*, Apr. 2000.

[2] A. Blair, T. Brown, K. M. Chugg, T. R. Halford, and M. Johnson. Barrage relay networks for cooperative transport in tactical MANETs. *MILCOM, IEEE*, Nov. 2008.

[3] A. Bletsas and A. Lippman. Implementing cooperative diversity antenna arrays with commodity hardware. *IEEE Comm. Mag.*, 44(12), Dec. 2006.

[4] G. J. Bradford and J. N. Laneman. An experimental framework for the evaluation of cooperative diversity. *Conference on Information Sciences and Systems*, pages 641–645, Mar. 2009.

[5] Y. J. Chang, M. A. Ingram, and S. R. Frazier. Cluster transmission time synchronization for cooperative transmission using software defined radio. *ICC Workshop on CoCoNet3*, June 2010.

[6] S. Jagannathan, H. Aghajan, and A. Goldsmith. The effect of time synchronization errors on the performance of cooperative MISO systems. *IEEE GlobeCom Workshops*, pages 102 – 107, Nov. 2004.

[7] J. W. Jung and M. A. Ingram. Residual-energy-activated cooperative transmission (REACT) to avoid the energy hole. *ICC Workshop on CoCoNet3*, June 2010.

[8] A. Kailas and M. A. Ingram. Alternating opportunistic large arrays in broadcasting for network lifetime extension. *IEEE Trans. on Wireless Comm.*, 8(6):2831–2835, June 2009.

[9] A. M. Karim and M. Othman. Packet synchronization structure with peak detection algorithm for MB-OFDM UWB. *Signal Processing, International Conference on*, 1, 16-20 2006.

[10] T. Korakis, M. Knox, E. Erkip, and S. Panwar. Cooperative network implementation using open-source platforms. *IEEE Comm. Mag.*, 47(2):134 –141, Feb. 2009.

[11] J. N. Laneman, D. N. C. Tse, and G. W. Wornell. Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *IEEE Trans. on Information Theory*, 50(12):3062–3080, Dec. 2004.

[12] J. N. Laneman and G. W. Wornell. Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks. *IEEE Trans. on Information Theory*, 49(10):2415–2425, Oct. 2003.

[13] R. Mudumbai, D. R. Brown, U. Madhow, and H. V. Poor. Distributed transmit beamforming: challenges and recent progress. *IEEE Comm. Mag.*, 47(2):102–110, February 2009.

[14] P. Murphy, A. Sabharwal, and B. Aazhang. On building a cooperative communication system: testbed implementation and first results. *EURASIP J. Wirel. Commun. Netw.*, 2009:1–9, 2009.

[15] B. Sirkeci-Mergen, A. Scaglione, and G. Mergen. Asymptotic analysis of multistage cooperative broadcast in wireless networks. *Information Theory, IEEE Trans. on*, 52(6):2531 – 2550, June 2006.

[16] L. Thanayankizil and M. A. Ingram. Reactive robust routing with Opportunistic Large Arrays. *ICC Workshops 2009*, June 2009.

[17] L. Thanayankizil, A. Kailas, and M. A. Ingram. Routing for wireless sensor networks with an opportunistic large array (OLA) physical layer. *Ad Hoc & Sensor Wireless Networks*, 8(1-2):79–117, 2009.