REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
09-09-2011	Final Technical Report	May 2007 - July 2010

4. TITLE AND SUBTITLE
Wireless Cooperative Networks: Self-Configuration and Optimization
Final Technical Report

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-07-1-0868

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Liuqing Yang

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Florida
Office of Engineering Research
343 Weil Hall, PO Box 116550
Gainesville, FL 32611

8. PERFORMING ORGANIZATION REPORT NUMBER
#4

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; distribution is Unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Cooperative signal processing is a promising technique to enhance system performance by employing virtual antenna arrays. In communications, cooperative transmission exploits space diversity via spatially separated relay nodes. Performance of such systems can be further improved by resource optimization. In this research, we investigated various factors influencing the resource optimization solutions and results in terms of the system error performance and throughput. Partly inspired by the benefits of cooperative communications, cooperative sensing is also drawing increasing interests lately. In such systems, a particularly critical issue is the waveform optimization among the cooperative nodes. In this direction, we developed the optimum and robust waveform designs respectively, and established the intrinsic connections between the mutual information (MI) and mean square error (MSE) measures in the sensing context. The sensitivity analysis for the optimum designs is also carried out.

15. SUBJECT TERMS
wireless sensor networks, wireless cooperative networks, resource optimization, ultra-wideband, localization, ranging

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	5	Liuqing Yang
					19b. TELEPHONE NUMBER *(Include area code)* (970)491-6215

Final Report

WIRELESS COOPERATIVE NETWORKS: SELF-CONFIGURATION AND OPTIMIZATION

Liuqing Yang

(Technical Point of Contact)

Dept. of Electrical and Computer Engineering

P.O. Box 116130

University of Florida

Gainesville, FL 32611

Tel: (352) 392-9469

Fax: (352) 392-0044

Email: lqyang@ece.ufl.edu

Ms. Roslyn S. Oleson

(Administrative Point of Contact)

Office of Engineering Research

College of Engineering

P.O. Box 116550

University of Florida

Gainesville, FL 32611-6550

Tel: (352) 392-9447 ext. 7

Fax: (352) 846-1471

Email: roleson@ufl.edu

Contents

A Abstract

This final report is to summarize our research conducted during the period of May 2007-July 2010 at University of Florida.

Cooperative signal processing is a promising technique to enhance system performance by employing virtual antenna arrays. In communications, cooperative transmission exploits space diversity via spatially separated relay nodes. Performance of such systems can be further improved by resource optimization. In this research, we investigated various factors influencing the resource optimization solutions and results in terms of the system error performance and throughput. Partly inspired by the benefits of cooperative communications, cooperative sensing is also drawing increasing interests lately. In such systems, a particularly critical issue is the waveform optimization among the cooperative nodes. In this direction, we developed the optimum and robust waveform designs respectively, and established the intrinsic connections between the mutual information (MI) and mean square error (MSE) measures in the sensing context. The sensitivity analysis for the optimum designs is also carried out. On these subjects, we have published/submitted 9 journal papers [1, 2, 3, 4, 5, 6, 7, 8, 9] and 17 conference papers [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26].

B Technical Results

B.1 Resource Optimization in Cooperative Communications

We consider two prevalent relay protocols for wireless sensor networks: decode-and-forward (DF) and amplify-and-forward (AF). To alleviate the channel estimation load at the receiver side, we consider differential modulation and demodulation for both protocols. We derive a tight upper bound of the error performance for the decode-and-forward case and a close approximation of the error performance for the amplify-and-forward case. Both are simple closed-form expressions accounting for arbitrary number of relays and possible existence of a direct wireless link from the source node to the destination node.

Based on these closed-form expressions, we then establish the optimum energy allocation strategy at the source and relay nodes given any source-relay-destination distances, and the optimum relay location selection for any energy distribution at the source and relay nodes. On top of these uncoupled optimizations, our error performance bound and approximation also allow for numerical search (as opposed to extensive simulations) of the global optimum operation condition which maximally reduces the total energy consumption or extends the communication range.

Our extensive analytical and simulated comparisons confirm that the optimized systems provide considerable improvement over un-optimized ones. We also show that the relay location optimization, which has been long neglected in related studies, may be more critical than the energy optimization. In addition, our joint optimization often results in considerably reduced power consumption at the relay nodes. This is favorable to wireless sensor networks where each node may have its own sensing data to transmit, since they can maximally conserve energy while helping others as relays.

B.2 Energy Saving and Coverage Extension

We evaluate the benefits of our optimization techniques in terms of the system energy saving and the coverage distance extension. Our analysis and simulations reveal several interesting results. For both DF and AF protocols, the optimized systems always outperform the unoptimized systems with either less energy consumption or longer transmission range. It is also noticed that the benefits of both energy and location optimizations vary a lot for different protocols, and with different system configurations. Uniform energy allocation and midpoint relay location are normally chosen as an initial system setup. For such a configuration with DF protocol, location optimization is more critical than energy optimization, and the unoptimized system receives prominent benefits from both optimizations, and tremendous system resources savings. For AF protocol, however, location and energy optimizations are equally important for the unoptimized system. It turns out that the uniform energy allocation and the midpoint relay location result in fairly good system performance, since it is reasonably close to the global optimum.

For other initial system setups, the optimization benefits are also distinct in AF and DF systems. In DF systems, more optimization benefits can be achieved when the relays are either close to the destination or have more transmit energy allocated to the relay(s). On the contrary, in AF systems, remarkable optimization benefits will be achieved when the relays are far from the midpoint, or when the relays are only able to transmit at low energy levels.

B.3 Factors Determining the Resource Optimization

We investigated the resource optimization problem in cooperative communications for four commonly adopted relaying systems: the amplify-and-forward (AF) protocol with coherent or differential modulation, and the decode-and-forward (DF) protocol with coherent or differential modulation. The closed-form symbol error rate (SER) and outage probability (OP) performances are derived for all four systems. Based on our previous work, we know that the location optimization is an important technique for system performance improvement. Therefore, location optimization is carried out for all four cooperative systems using both SER and OP optimization metrics. The comparisons among the optimization solutions and results for all four systems with both metrics revealed the influence of different system parameters, which can be used to guide the optimization strategy selection in practice. The comparison results are summarized as follows.

Optimization Metric: Even though SER and OP evaluate the system performance from two very different aspects, the four systems surprisingly share the same optimization solutions. This suggests that SER and OP are identical from the resource optimization perspective; that is, the SER-optimized relay system is also OP-optimum. On the other hand, while SER can be formulated in closed- form for arbitrary number of relays, the OP is only available for single-relay AF systems. Therefore, SER is a more convenient metric for resource optimization in cooperative systems with arbitrary number of relays.

Modulation Type: Regarding different modulation types, the coherent and differential systems have similar performance with identical diversity gains, leading to identical optimization solutions. This observation implies that the optimized coherent system can also adopt differential modulation with the same system setting while still achieving the optimum performance.

Relaying Protocol: On the other hand, with the same modulation type, AF and DF protocols result in very different optimization results. However, this difference decreases as L increases. We also observe that, in AF systems, the relay-destination link is more critical than in DF systems. Hence, for the same system setup, the optimized AF systems require relays to move closer to the destination than DF systems.

B.4 Waveform Optimization in Cooperative Sensing

Information theory, and particularly the MI, has provided fundamental guidance for communications research. However, the practical meaning of MI in the sensing context remains unclear to date. Previous work shows that under the white noise assumption, the optimum water-filling scheme simultaneously maximizes the MI and minimizes the estimation minimum mean square error (MMSE). Such an equivalence, however, does not hold when the target parameter statistics are not perfectly known. To further the understanding of the practical meaning of MI and to establish a connection between the MI and commonly adopted MSE measures for cooperative sensing, we consider the general colored noise, incorporate the normalized MSE (NMSE), and develop joint robust designs for both the transmitter (waveforms) and the receiver (estimator) under various target and noise uncertainty models. Our results show that: i) the optimum waveform designs resulted from the MI, MMSE and NMSE criteria are all different; and ii) compared to MMSE, the NMSE-based designs share more similarities with the MI-based ones, especially when the target and noise statistics are not perfectly known.

Since the optimum waveform designs depend on the ideally known target power spectrum density (PSD) assumption, a small target PSD error might introduce huge disturbance to the optimum designs. The robustness of our optimum designs and the sensitivity comparison among the three criteria consist of an intriguing problem. In order to address these issues, we perform the error sensitivity analysis not only at the multiple cooperative nodes in terms of the waveform designs, but also at the receiver in terms of the overall estimation performance. The analyses show that the NMSE-based waveform design solution is relatively more sensitive than its MMSE- and MI-based counterparts. At the receiver side, the NMSE performance is compared among the three criteria. While all three criteria do not show significant performance deterioration, the NMSE-based design is affected most around the PSD error threshold, which is consistent with the results obtained at the cooperative nodes.

C References

[1] W. Cho, R. Cao, and L. Yang, "Optimum resource allocation for amplify-and-forward relay networks with differential modulation," *IEEE Trans. on Signal Processing*, vol. 56,

no. 11, pp. 5680–5691, November 2008.

[2] W. Cho and L. Yang, "Optimum resource allocation for relay networks with differential modulation," *IEEE Trans. on Communications*, vol. 56, no. 4, pp. 531–534, April 2008.

[3] R. Cao and L. Yang, "Optimum recourse allocation in distributed MIMO systems," *International Journal of Distributed Sensor Networks*, vol. 5, no. 1, January 2009 (invited).

[4] D. Duan, F. Qu, L. Yang, A. Swami, and J. C. Principe, "Modulation selection from a battery power efficiency perspective," *IEEE Trans. on Communications*, vol. 58, no. 7, pp. 1907–1911, July 2010.

[5] D. Duan, L. Yang, and J. C. Principe, "Cooperative diversity of spectrum sensing for cognitive radio systems," *IEEE Trans. on Signal Processing*, vol. 58, no. 6, pp. 3218–3227, June 2010.

[6] W. Zhang and L. Yang, "Communications-inspired sensing: a case study on waveform design," *IEEE Trans. on Signal Processing*, vol. 58, no. 2, pp. 792–803, February 2010.

[7] W. Zhang, D. Duan, and L. Yang, "Relay selection from a battery energy efficiency perspective," *IEEE Trans. on Wireless Communications*, 2011, (accepted).

[8] R. Cao, F. Qu, and L. Yang, "Relay-aided Cooperative Communications for Underwater Acoustic Networks," *IEEE Journal of Oceanic Engineering* (submitted).

[9] R. Cao and L. Yang, "Resource Optimization for Cooperative Networks: Effects of Optimization Metric, Modulation Format and Relaying Protocol," *IEEE Transactions on Wireless Communications* (submitted).

[10] W. Cho and L. Yang, "Energy and location optimization for relay networks with differential modulation," in *Proc. of 25th Army Science Conference*, Orlando, FL, November 27–30, 2006.

[11] Q. Zhang, W. Cho, G. E. Sobelman, L. Yang, and R. Voyles, "TwinsNet: a cooperative MIMO mobile sensor networks," in *Lecture Notes in Computer Science*, vol. 4159, 2006, pp. 508–516.

[12] W. Cho and L. Yang, "Optimum energy allocation for cooperative networks with differential modulation," in *Proc. of MILCOM Conf.*, Washington, DC, Oct 23-25, 2006.

[13] W. Cho and L. Yang, "Distributed differential schemes for cooperative wireless networks," in *Proc. of Intl. Conf. on ASSP*, Toulouse, France, May 15-19, 2006.

[14] W. Cho and L. Yang, "Differential modulation schemes for cooperative diversity," in *Proc. of IEEE International Conference on Networking, Sensing and Control*, Ft. Lauderdale, FL, April 23-25, 2006.

[15] R. Cao and L. Yang, "Optimum resource allocation in distributed mimo systems," in *International Symposium on Advances in Computer and Sensor Networks and Systems*, Zhengzhou, China, April 7-10 2008 (invited).

[16] W. Cho and L. Yang, "Resource allocation for amplify-and-forward relay networks with differential modulation," in *Proc. of Global Telecommunications Conf.*, Washington, D.C., pp. 1668–1672.

[17] W. Cho and L. Yang, "Joint energy and location optimization for relay networks with differential modulation," in *Proc. of Intl. Conf. on Acoustics, Speech, and Signal Processing*, vol. 3, Honolulu, Hawaii, April 15-20, 2007, pp. 153–156.

[18] W. Cho, R. Cao, and L. Yang, "Optimum energy allocation in cooperative networks: a comparative study," in *Proc. of MILCOM Conf.*, Orlando, FL, Octoboer 29–31 2007.

[19] F. Qu, D. Duan, L. Yang, and A. Swami, "Signaling with imperfect channel state information: a battery power efficiency comparison," in *Proc. of MILCOM Conf.*, Orlando, FL, October 29-31, 2007.

[20] R. Cao and L. Yang, "Practical issues on resource optimization for relay networks," in *Proc. of Conference on Info. Sciences and Systems.*, The Princeton Univ., Princeton, March 19-21, 2008.

[21] W. Cho and L. Yang, "Performance analysis of cooperative netwroks with differential unitary space time coding," in *Proc. of Intl. Conf. on Acoustics, Speech, and Signal Processing*, Las Vegas, NV, March 30–April 4 2008.

[22] D. Duan, L. Yang, and J. C. Principe, "Cooperative diversity of spectrum sensing in cognitive radio networks," in *Proc. of Wireless Communications and Networking Conf.*, Budapest, Hungary, April 5-8, 2009.

[23] D. Duan, F. Qu, L. Yang, A. Swami, and J. C. Principe, "Modulation selection from a battery power efficiency perspective," *IEEE Trans. on Comm.*, vol. 58, no. 7, pp. 1907–1911, July 2010.

[24] R. Cao and Y. Yang, "What affects resource optimization of cooperative networks?" in *Proc. of Wireless Communications and Networking Conf.*, Budapest, Hungary, April 5-8, 2009.

[25] R. Cao, F. Qu, and L. Yang, "On the capacity and system design of relay-aided underwater acoustic communications," in *Proc. of Wireless Communications and Networking Conf.*, Sydney, Australia, April 18-21, 2010.

[26] W. Zhang and L. Yang, "Sensitivity analysis of the optimum waveform design for target estimation in MIMO sensing," in *Proc. of Wireless Communications and Networking Conf.*, Sydney, Australia, Apr 2010, pp. 1–6.