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Research Letter

A Low-Overhead Cooperative Retransmission Scheme for IR-UWB Networks

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The UWB unique properties such as fine ranging and immunity to small scale fading are utilized in order to exploit the multiuser diversity in UWB networks. The optimal cooperation strategies in the absence of control packet overhead are analyzed in the proactive and reactive settings. It is shown that the proposed method achieves a considerable diversity gain while minimizing the overhead of control packet exchange that is required for coordination among the relays.

1. Introduction

Due to the large bandwidth occupied by pulses, UWB signals are considered robust to small scale fading effects. In addition, UWB enables high accuracy ranging which can be used for the design of location-aware MAC and routing mechanisms. We exploit these properties of UWB, that is, availability of ranging information and immunity to small scale fading, in the design of an *U*WB-based *Co*operative *R*etransmission *S*cheme (*UCoRS*) [1].

Most of the existing distributed relay selection schemes, such as [2–4] rely on the Priority-Based Backoff Timer (*PBT*) mechanism to discover which relay is the best one at a time instance by sending a flag message. We note that like *PBT*, the other existing mechanisms such as *CMAC* [5] also require the exchange of the RTS/CTS and other control messages for every transmission. These cooperative methods may be inefficient for UWB networks. This is because the standard IR-UWB MAC protocol is ALOHA [6] and the exchange of RTS/CTS packets is not required prior to the data transmission in UWB. Furthermore, it is preferred to exchange fewer control packets due to the complex and costly UWB receiving procedure.

2. System Model

Figure 1 shows the system model. As can be seen, there are a source S and a destination D, and N relays R_i, $i = 1, 2, \ldots, N$, in a slotted time domain, and each time slot consists of 2 subslots. At the transmission subslot (Tx), the source node sends data to its destination. At the Cx subslot, the relays retransmit the source data. In particular, the ith relay, R_i, decides to cooperate (i.e., retransmit the data) with probability a_i.

Since accurate ranging information is available through UWB physical layer, we also presume that when R_i finds its distance to S and D, it broadcasts a packet to inform other nodes about these ranging information. Note that as long as the nodes do not move, the process of ranging and informing other nodes should be performed only once, which incurs much less overhead compared to sending control packets for *every* transmission.

The link success probabilities are denoted by P_i and Q_i, as can be seen in Figure 1. The success probability of the S-D link is denoted by P_0. To calculate these values, we note that in time-hopping pulse position modulation, TH-PPM, the transmitted signal by node i is given by $s^i(t) = \sum_{j=-\infty}^{\infty}\sqrt{E_p}\omega(t - jT_f - c_j^i T_c - \delta b^i_{\lfloor j/N_S \rfloor})$, where E_p is the transmission energy per pulse, T_f and T_c are the frame and chip durations, $b^i_{\lfloor j/N_S \rfloor} \in \{0, 1\}$ is the information bit to be sent, $\omega(t)$ is the monocycle pulse, and δ determines the time shift in the chip when the data bit is 1. Each frame consists of N_h chips, that is, $T_f = N_h T_c$. Moreover, each bit is repeated in N_S frames with different time hopping codes, $c_j^i \in \{0, 1, \ldots, N_h - 1\}$, which results in additional (random) time shifts and hence increases the pulse immunity to interference.

The received signal from user i at node j is given by [7] $r^{ij}(t) = \alpha^{ij} \sum_{c=1}^{C} \sum_{l=1}^{L} \beta_{cl} s^i(t - \tau_{cl}) + n(t)$, where $n(t)$ is AWGN with the power spectral density $N_0/2$, and α^{ij} denotes the i-j link gain. Since UWB pulses are robust to small scale fading effects, we consider only the channel pathloss, as defined in [1, 6]. Then, the bit error probability (BEP) in the absence of interference can be approximated by $P_{\text{be}}(d_{ij}) = (1/2)\text{erfc}(\sqrt{(\alpha^{ij} E_p N_S / 2N_0)(1 - \rho(\delta))})$ [7], where $\rho(\delta)$ is the autocorrelation function of the monocycle pulse, $\omega(t)$. From the above-mentioned model, the probability that a packet with length L bits is successfully transmitted can be represented as follows:

$$P_s(d) = 1 - \left(1 - P_{\text{be}}(d)\right)^L. \quad (1)$$

This equation can be used to determine the values of P_i and Q_i as a function of the relays' distances to S and D. Having obtained P_i and Q_is from (1), the next problem is to find the cooperation probabilities a_i in order to maximize the S-D throughput.

3. Analysis

We assume that the packet level collision occurs if the signal strength of more than one packet is above the threshold at the receiver. Therefore, D successfully receives a useful data packet if either the S-D transmission in the Tx subslot is successful, or the transmission from one and only one of the relays in the Cx subslot is successful.

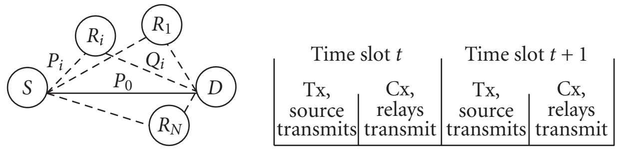
We consider two different settings, namely, the proactive and reactive modes. In the proactive mode, the decision is made prior to the source transmission. In the reactive mode, all relays listen for the data first and then decide to cooperate. Note that since message exchange between relays is not performed in *UCoRS*, a relay R_i is unable to find out the set of relays which have successfully decoded the packet from S at time slot t, denoted by $F(t)$. In fact, the global optimum of the relay selection problem would be obtained if $F(t)$ were available to the nodes.

In the proactive case, the expected success probability in a time slot is given by

$$U(A) = P_0 + (1 - P_0) \sum_{i=1}^{N} \left[a_i P_i Q_i \prod_{j=1, j \neq i}^{N} (1 - a_j P_j Q_j) \right]. \quad (2)$$

In order to find the optimal solution of (2), we use Lemma 1 in the Appendix. The following theorem gives the optimal solution.

Theorem 1. *Consider a cooperative network with one S-D pair and N relays. The optimal cooperation strategy to maximize the S-D throughput (U(A) in (2)) is* $A^{(K)} = \{a_i = 1, i \leq K; a_i = 0, i > K\}$, *where K satisfies:* $\sum_{i=1}^{K-1}(P_iQ_i/(1 - P_iQ_i)) < 1$, *and* $\sum_{i=1}^{K}(P_iQ_i/(1 - P_iQ_i)) \geq 1$, *where relays are sorted in descending order according to the values of* P_iQ_i *(i.e.,* $i \leq j \Leftrightarrow P_iQ_i \geq P_jQ_j$*); and* $A^{(K)}$ *denotes a binary vector whose first Kth elements are* 1. *(Proof is straightforward from Lemma 1.)*



(a) Network model (b) Time slot model

Figure 1: System model.

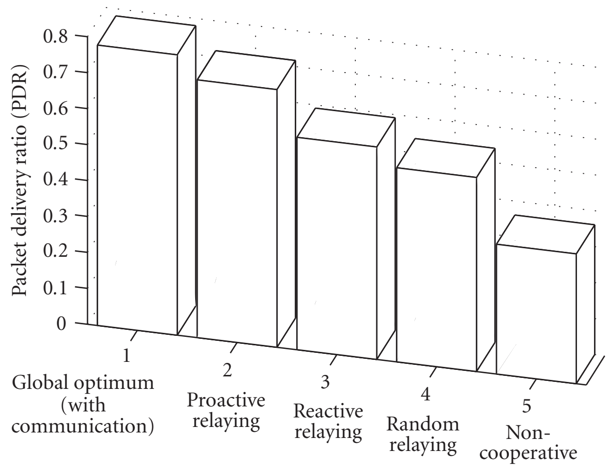


Figure 2: Comparison of packet delivery ratio (PDR) for different schemes.

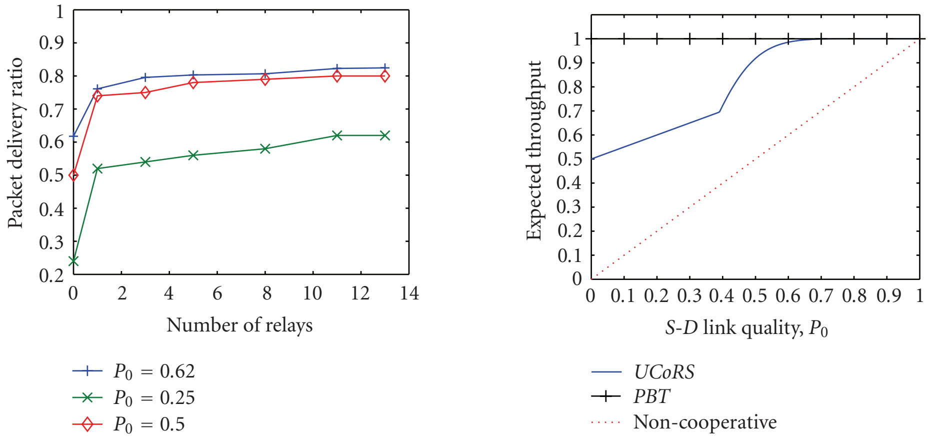
Here, we mention that if $P_1Q_1 \geq 0.5$, then $K = 1$, and only R_1 will be active. In this special case, the result is in agreement with [3]. The reactive and global optimum cooperation strategies can be derived using the same reasoning as Theorem 1, as discussed in detail in [1].

4. Performance Evaluation

Figure 2 compares the packet delivery ratio (PDR) for different scenarios. As can be seen, the proactive performance is near to the maximum achievable throughput. Furthermore, as expected, both reactive and proactive methods outperform the noncooperative case.

Figure 3(a) shows the effect of increasing the number of relays on the achieved PDR in *UCoRS* for different S-D link qualities. As can be seen, adding one relay can significantly increase the PDR of the direct link. However, the achieved PDR in *UCoRS* is upper bounded by a function of d_{SD}, regardless of number of available relays.

Figure 3(b) shows the asymptotic achievable throughput of *UCoRS*, *PBT*, and noncooperative schemes as a function of P_0 when $N \rightarrow \infty$. As stated previously, the throughput advantage of *PBT* over *UCoRS* is at the expense of control packet exchange for every data transmission, which may not be efficient in UWB. More details can be found in [1].



(a) Effect of increasing number of relays on PDR

(b) Asymptotic throughput achievable by *UCoRS* and *PBT* as $N \to \infty$

Figure 3: Simulation results.

5. Conclusion

We introduced *UCoRS*, a simple *U*WB-based *Co*operative *R*etransmission *S*cheme, that utilizes the unique properties of IR-UWB technology for achieving multiuser diversity in UWB in the proactive and reactive settings. The amount of control packet overhead is minimized in *UCoRS* in order to eliminate the corresponding energy cost at the UWB receivers.

Appendix

Lemma 1. *Assume a set of variables* $Z = \{z_i\}$, $i = 1, 2, \ldots, n$, *that can take on real values between* 0 *and* $1 > m_1 \geq m_2 \geq \cdots \geq m_n$, *respectively. Then, the maximum value of* $X(Z) = \sum_{i=1}^{n}(z_i)\prod_{j \neq i}(1 - z_j)$ *is obtained when* $z_i = m_i$, $i \leq K$, *and* $z_i = 0$, $i > K$, *where* K *satisfies* $\sum_{i=1}^{K}(m_i/(1 - m_i)) \geq 1$, *and* $\sum_{i=1}^{K-1}(m_i/(1 - m_i)) < 1$.

Proof. Taking the partial derivative of $X(Z)$, we have

$$\begin{aligned}\frac{\partial X(Z)}{\partial z_i} &= \prod_{j \neq i}(1 - z_j) - \sum_{j \neq i}\left(z_j \prod_{k \neq i,j}(1 - z_k)\right) \\ &= \prod_{j \neq i}(1 - z_j)\left(1 - \sum_{j \neq i}\frac{z_j}{1 - z_j}\right).\end{aligned} \tag{A.1}$$

Therefore, $\partial X(Z)/\partial z_i > 0 \Leftrightarrow \sum_{j=1, j \neq i}^{n}(z_j/(1 - z_j)) < 1$, and $\partial X(Z)/\partial z_i > \partial X(Z)/\partial z_j \Leftrightarrow z_i > z_j$. According to these two results, in order to maximize $X(Z)$, the K "best" variables (with looser bounds) should be set to their maximum values and other variables should be set to 0. The required conditions on $K$are also clearly observed from the above-mentioned equations. Note that if $m_1 \geq 0.5$, then $K = 1$. □

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Cooperative communication is an overwhelming research topic in wireless networks. The notion of cooperative communication is to enable transmit and receive cooperation at user level by exploiting the broadcast nature of wireless radio waves so that the overall system performance including power efficiency and communication reliability can be improved. However, due to the half-duplex constraint in practical systems, cooperative communication suffers from loss in spectral efficiency. Network coding has recently demonstrated significant potential for improving network throughput. Its principle is to allow an intermediate network node to mix the data received from multiple links for subsequent transmission. Applying the principle of network coding to wireless cooperative networks for spectral efficiency improvement has recently received tremendous attention from the research community. *Physical-layer network coding* (PLNC) is now known as a set of signal processing techniques combining channel coding, signal detection, and network coding in various relay-based communication scenarios, such as two-way communication, multiple access, multicasting, and broadcasting. To better exploit this new technique and promote its applications, many technical issues remain to be studied, varying from fundamental performance limits to practical implementation aspects. The aim of this special issue is to consolidate the latest research advances in physical-layer network coding in wireless cooperative networks. We are seeking new and original contributions addressing various aspects of PLNC. Topics of interest include, but not limited to:

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We are today witnessing an explosive growth in the deployment of wireless communication services. At the same time, wireless system designers are facing the continuously increasing demand for capacity and mobility required by the new user applications. The scarcity of the radio spectrum, densely allocated by the regulators, is a major bottleneck in the development of new wireless communications systems. However actual spectrum occupancy measurements show that the frequency band scarcity is not a result of the heavy usage of the spectrum, but is rather due to the inefficient static frequency allocation pursued by the regulators.

Dynamic spectrum access has been proposed as a new technology to resolve this paradox. Sparse assigned frequency bands are opened to secondary users, provided that interference generated on the primary licensee is negligible. Even if the concept constitutes a real paradigm shift, it is still unclear how the dynamic spectrum access can operate efficiently and how it can be implemented cost-effectively.

Scope. Original contributions are solicited in all aspects of dynamic spectrum access related to the integration of the technology in a real communication system. The special issue should give clear advice on how to make dynamic spectrum access work in practice. Topics of interest include, but are not limited to:

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  - Adaptive coding and modulation for interference avoidance
  - Beamforming and MIMO for interference avoidance
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  - Game theory for dynamic spectrum access
  - Genetic and artificial intelligence-inspired algorithms
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Recent advances in wireless communications and computing technologies have paved the way for the proliferation of ubiquitous infrastructure and ad hoc wireless networks, enabling a broad range of applications ranging from protection of critical infrastructure to protection of wireless communications, from environment monitoring to health care, and from conducting business to improving quality of life. The need to deal with the complexity and ramifications of the fast-growing number of mobile users and services intensifies the interest in the development of fundamental principles, novel algorithmic approaches, rigorous and repeatable design methodologies, and systematic evaluation frameworks for the next-generation wireless networks.

The proposed special issue solicits technical papers that describe previously unpublished research work, visionary approaches, and future research directions dealing with effective and efficient algorithm design and analysis, reliable and secure system development and implementations, experimental study and test bed validation, as well as new application exploration in wireless networks. Topics of interest include, but are not limited to, the following:

- Wireless networks for cyber-physical systems (transportation, health care, civil infrastructure, etc.)
- Theoretical frameworks and efficient algorithm design
- PHY/MAC/Routing protocols
- Application and design of wireless ad hoc and sensor networks
- Experimental test-beds, models, and case studies

Call-for-papers for the proposed special issue will be distributed to wireless network communities. We will also encourage authors of WASA'09 (The Fourth International Annual Conference on Wireless Algorithms, Systems and Applications) to submit their work to this special issue. WASA'09 addresses similar problems of the special issue, including the research and development efforts of various issues in the area of algorithms, systems, and applications for the current and next-generation infrastructure and ad hoc wireless networks.

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