Distributed Cooperative Routing for UWB Ad-Hoc Networks

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***Abstract*— Ultra wide band (UWB) ad-hoc networks have attracted much research attention in recent years. This paper proposes and investigates a new distributed cooperative routing strategy that forwards data via a multi-hop route with the best instantaneous quality among available routes in UWB ad-hoc networks. The new method combines the physical and medium-access-control (MAC) layer mechanisms to identify the best route in a cooperative and distributed way. Using an example of a two-hop relay network where data from a source node can be forwarded by several possible relays to the destination node, we study two related issues. First, to support the cooperative and distributed routing, we devise a new, efficient estimation algorithm for received signal-to-noise ratio (SNR), which is used to determine UWB link/route quality. The estimation method is based on the fact that UWB links often adopt pulse position modulation (PPM) for transmissions, and in that context the transfered data in the received signal can be simplified as *one-dimension* binary phase shift keying (BPSK) data over a complex, i.e. *two-dimension*, noise channel. The algorithm is unbiased and its estimation errors are lower than existing algorithms. Second, a distributed cooperative routing scheme is proposed. Each relay node uses the carrier sensing with deterministic backoff period as the MAC protocol. The backoff period is chosen by each relay such that the higher the quality of the associated source-relay-destination route, the shorter is the backoff time. Combining this with carrier sensing, the route with the best instantaneous quality is used for data forwarding. To avoid hidden-terminal problems among relays, the scheme also requires the destination node to send a quick acknowledgment to the relays upon receiving the forwarded data. Simulation results show that even without any feedback about the relay-destination link quality from the destination node to relays and using only its statistical characteristics, the proposed scheme still has *3 dB* improvement in performance as compared to a random route selection. When having 1-bit feedback, the proposed scheme can achieve *full* diversity and the overall performance is only *2 dB* lower than that with true relay-destination link quality.**

I. Introduction

Wireless ad-hoc networks have been a very active area of research in recent years because they can be used to support communications in situations where any other communication infrastructure is not available or is hard to deploy [1]. The potentials and applications of ad-hoc networks are further highlighted after the ultra wide band (UWB) in the radio frequency spectrum is allocated for unlicensed use in many countries [2][3]. As a result, several major research projects [2][3], including the EU PULSERS research project [4], have been launched to study UWB ad-hoc networks with a goal towards massive UWB applications in the near future [6][7][8][9].

In an UWB ad-hoc network, the broadcasting nature of wireless media results in multiple possible routes when transfering data from a source node to a destination node, among which neighbouring UWB links interfere with each other. At any given point in time, some routes have high quality (e.g., in terms of signal-to-noise ratio, SNR), while others are poor. Therefore, it is advantageous to employ cooperative transmission strategies for efficient utilization of possible radio resources and performance improvement [10][11]. The main idea of these cooperative strategies is to transport data through multiple nodes in the network such that these nodes work cooperatively to improve the overall network throughput, error and/or delay performance.

A snapshot of ad-hoc networks is two-hop relay networks, which include a pair of source and destination nodes and multiple relay nodes to forward data from the source to the destination. The relay nodes can also be data source and destination nodes at different points in time. For these relay networks with parallel routes, an efficient and simple cooperative transmission strategy is the instantaneous quality-based relay route selection, in which the route with the highest quality is selected for data relaying. Such relay route selection serves the same purpose as the typical routing algorithms in wired networks, except that the former is based on instantaneous link quality and combined cross-layer protocol functions among nodes in a distributed manner, which is thus referred to as cooperative routing.

Recent studies to the problem of distributed cooperative routing focus on the techniques for collision avoidance mechanism and quality representation of relay routes, where assuming Rayleigh flat-fading links are used [12] [13]. In [12], a carrier-sensing technique is used as the basis of the collision avoidance mechanism. All relay nodes prepare to forward the received data from a source node to a destination node, but with different backoff times. Here the backoff time refers to a period of time each node delays its transmission by. [12] suggests exponential backoff times with their means adversely proportional to the route quality for ease of performance analysis. In [13], a pair of request-to-send (RTS) and clear-to-send (CTS) messages are exchanged between the source and destination nodes to enable link quality measurement and avoid collisions. However, these two techniques are not

This work was supported by the EU PULSERS research project.

efficient in common situations. For example, when relay nodes are blocked from each other by obstacles, the carrier sensing technique does not work well due to hidden-terminal problems. Moreover, the randomness introduced in the mapping from route quality to backoff time is not necessary. The source-destination RTS-CTS technique also represents unnecessary exchange of control information. Meanwhile, many other supporting techniques for the aforementioned instantaneous quality-based route selection are still under investigation. For example, how could one optimally represent and estimate the quality of UWB links? How should we efficiently represent and utilize the end-to-end relay route quality, especially with different data forwarding policies such as decode-and-forward or amplify-and-forward? How can we devise and combine the physical (PHY) and MAC layer information for efficient routing decision? These questions as well as the relevant research tasks in the EU PULSERS research project (see [4] as well as [5]) have motivated our work reported here.

The contributions of this paper can be summarized as follows:

- UWB links often adopt pulse position modulation (PPM) for transmissions. In that context, the transferred data in the received signal, after correlation and/or rake combining, can be simplified as *one-dimension* binary phase shift keying (BPSK) data over a complex, i.e. *two-dimension*, noise channel. To support the cooperative and distributed routing algorithm, we devise a new, efficient algorithm to estimate received signal-to-noise ratio (SNR). The new algorithm utilizes for the first time in such an issue the difference between the one-dimensional BPSK data and the two-dimensional complex noise. The estimation method is unbiased over a large range of received SNR of practical interest. Our performance results reveal that its estimation errors are lower than existing algorithms and very close the Cramer-Rao bound [19].
- By using information and protocol functions at the PHY and MAC layers, a distributed cooperative routing scheme is proposed for UWB two-hop relay networks. Each relay node uses the carrier sensing with deterministic backoff period as the MAC protocol. The backoff period is chosen by each relay such that the higher the quality of the associated source-relay-destination route, the shorter is the backoff time. Combining this with carrier sensing, the route with the best instantaneous quality is used for data forwarding. To avoid hidden-terminal problems among relays, the scheme also requires the destination node to send a quick acknowledgment to the relays upon receiving the forwarded data. Simulation results show that even without any feedback on relay-destinatin link quality from the destination node to relays and using only its statistical characteristics, the proposed scheme still has 3dB improvement in performance as compared to a random route selection. When having 1-bit feedback, the proposed scheme can achieve full diversity and the overall performance is only 2dB lower than that with true relay-destination link quality.

The rest of this paper is organised as follows. In section II, the network scenario under investigation is described. In section III, a new algorithm for estimation of received SNR is proposed for the UWB links using the pulse position modulation. In section IV, a feasible distributed cooperative routing scheme is presented. In section V, simulation studies are conducted to evaluate the proposed received SNR estimation algorithm for UWB links and the proposed cooperative routing scheme. Finally, conclusions are given in section VI.

II. Network Scenario Under Investigation

The network scenario under inverstigation includes a pair of source-destination nodes and M relay nodes that constitute M parallel relay routes, all with UWB links, see Fig.1. The scenario represents a snapshot of an ad-hoc network and the role of source, destination and relay nodes can change over time. The source node, labelled as S, broadcasts data to all relay nodes, labelled as from R_1 to R_M. The direct transmission between the source and destination nodes is not guaranteed because of the distance or obstacles between them. To take advantage of diversity of various radio routes, one of the relay nodes with the best instantaneous route quality is selected to forward the received data to the destination node, labelled as D, meanwhile all other relay nodes prohibit their data forwarding by the MAC protocol.

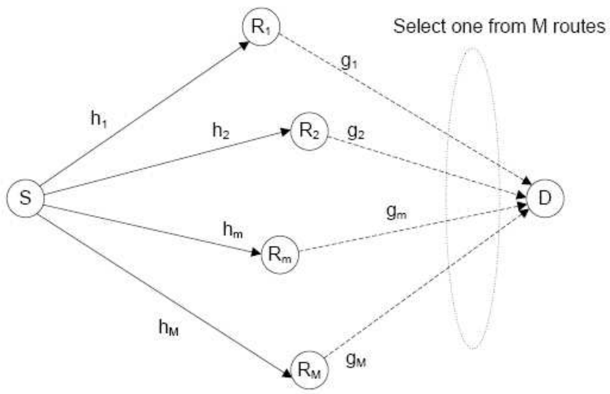

Fig. 1. Considered network scenario: a UWB parallel relaying network

Assuming that all UWB links adopt the pulse position modulation (PPM) [14][15] for transmission, we can represent the received signal at each relay node and destination node as

$$\tilde{r}_m(t) = \sum_k \sqrt{P_s} p(t - kT_b - \frac{1 - s_k}{2}\delta) h_m + \tilde{n}_m(t) \quad (1)$$

$$\tilde{r}_d(t) = \sum_k \sqrt{P_s} p(t - kT_b - \frac{1 - s_k}{2}\delta) g_m + \tilde{n}_d(t) \quad (2)$$

where $p(t)$ is the UWB pulse waveform that has normalized energy $\int_{-\infty}^{+\infty} p^2(t)dt = 1$, T_b is the data bit duration, $s_k \in [-1, 1]$ is the transmitted data bit, δ is a small time offset, P_s is the transmit power of data symbols, and h_m and g_m are link gains, while $\tilde{n}_m(t)$ and $\tilde{n}_d(t)$ are white and circularly rotated complex Gaussian noise with zero mean.

III. Estimate Received SNR of UWB Link

Received SNR is an important measure for channel quality. Besides the need of the cooperative and distributed routing in this work, many other resource allocation techniques in communication systems also use received SNR estimates for performance optimization. Below, let us recall the data detection process for UWB links and then show the correspondence between UWB links and BPSK data over complex noise channels.

The best pre-processing for UWB data detection is the pulse waveform matched filtering, carried out by a correlation unit. The output of such correlation unit is

$$r_m(k) = \int_{kT_b}^{(k+1)T_b} \tilde{r}_m(t)v(t-kT_b)dt = s(k)h_m + n_m(k) \tag{3}$$

$$r_d(k) = \int_{kT_b}^{(k+1)T_b} \tilde{r}_d(t)v(t-kT_b)dt = s(k)g_m + n_d(k) \tag{4}$$

where $v(t)$ is the system function of the correlation unit, such that its correlation with $p(t)$ is an impulse function with unit energy. $s(k)h_m$ and $s(k)g_m$ are the transmitted signal that is like BPSK data, while $n_m(k)$ and $n_d(k)$ are complex received noise, which also is white and circularly rotated complex Gaussian noise with zero mean.

We are interested in the difference between the one-dimensional BPSK data and the two-dimensional complex noise, which makes it possible to propose a second order statistics (SOS)-based algorithm to clearly distinguish data and noise from their additive mixture.

For simplicity, we rewrite the correlation outputs and drop the node indices from these variables

$$r(k) = s(k)h + n(k), k = 1, ..., K \tag{5}$$

Two measures could be obtained as follows

$$M_1 = |\sum_{k=1}^{K} r^2(k)| \approx |E[r^2(k)]| = P_s|h|^2 \tag{6}$$

$$M_2 = \sum_{k=1}^{K} |r(k)|^2 \approx E[|r(k)|^2] = P_s|h|^2 + \sigma_n^2 \tag{7}$$

where σ_n^2 is the variance of the received noise. The received SNR is then obtained as

$$\widehat{\mathsf{SNR}} = \frac{M_1}{M_2 - M_1} \approx \frac{P_s|h|^2}{\sigma_n^2} = \mathsf{SNR} \tag{8}$$

It is easily seen that the estimated received SNR is unbiased for any finite K, and has a lower estimation error than the higher order statistics (HOS)-based algorithms. This is because that it is well known when given a set of observed data, their SOS statistical measures have higher estimation accuracy as compared to their HOS counterparts.

IV. A Distributed Cooperative Routing Scheme

A. Route Selection and Collision Avoidance Mechanism

In the proposed scheme, each relay node uses the carrier sensing with deterministic backoff period as the MAC protocol. Immediately after receiving the last symbol of data from the source node, each relay node senses the channel and determines the quality of its source-relay-destination route in terms of bit error rate (BER). The backoff period for each relay is chosen such that the higher the quality for its source-relay-destination route, the shorter the backoff time is. Each relay continues to monitor the channel activity and starts its data forward at the end of the backoff period, if no other relay node has started its data forwarding. On the other hand, the relay node will refrain from forwarding if another node has started already. As a result, the selection of backoff periods at various relay nodes ensures that the relay with the best route quality will be the one responsible for forwarding the data to the destination node. To further avoid hidden-terminal problems among relays caused by obstacles, the scheme also requires the destination node to send a quick acknowledgment to the relays upon receiving the forwarded data. All relay nodes refrain from further data forwarding when such an acknowledgment is received from the destination node. The end result is that the optimal route is used for data transport in a distributed manner by combining the PHY and MAC functions.

In the following sectons, we discuss how the BER for each route is obtained from the estimates of link received SNR for the commonly used data forwarding policies. Then, the ways to feedback link quality information from the destination node to the relays are presented.

B. Represent Relay Route Quality

A data route is composed of a source-relay link and a relay-destination link. Relay nodes may adopt either the decode-and-forward and amplify-and-forward policy to forward data to the destination node. Depending on the policy in use, the end-to-end route quality can be represented as a function of two links' quality. For these reasons, the bit error rate (BER), rather than the received SNR, is a more appropriate measure for communication quality. We present the relay route quality in terms of BER for both policies as follows.

When using the decode-and-forward at relay node m, the BER of relay route m can be represented as

$$\mathsf{BER}_m = \mathrm{Q}(\mathsf{SNR}_{sm}) + \mathrm{Q}(\mathsf{SNR}_{md}) - \mathrm{Q}(\mathsf{SNR}_{sm})\mathrm{Q}(\mathsf{SNR}_{md}) \tag{9}$$

while if using the amplify-and-forward policy, its BER is

$$\mathsf{BER}_m = \mathrm{Q}(\frac{\mathsf{SNR}_{sm}\mathsf{SNR}_{md}}{1 + \mathsf{SNR}_{sm} + \mathsf{SNR}_{md}}) \tag{10}$$

where the indices sm and md are used to refer to the source-relay link and the relay-destination link involving relay m, respectively, and Q(.) is the error function.

In proposed scheme, the backoff time of each relay node is deterministically selected from the above BER measure, in a suitable directly proportional order. Each relay node collects the received SNRs of its source-relay link and its relay-destination link, to obtain the BER of its end-to-end route. The former received SNR can be estimated directly at each relay node when receiving and detecting data from source node, the latter however cannot be obtained directly.

In this work, we consider three possible indirect ways for each relay node to determine the relay-destination link quality in terms of received SNR: i) the link quality is known only through *a priori* statistical information on channel fading; ii) the link quality is provided by the destination node in a form of feedback with limited precision; and iii) the link quality is estimated by the reception in the reverse direction, assuming that the two-way communications use the same frequency, as in the time-division duplex (TDD) operations. Note that the last way for determining the link quality, i.e. assuming the correct received SNR of relay-destination link is known at each relay node, is to serve as a benchmark for comparison with the other two methods. As revealed in the following, we focus on the impacts of channel feedback from the destination node in the following.

C. Represent Relay-Destination Link Quality at Relay Node

1) Without Feedback: In this case the relay-destination link quality is estimated based on the *a priori* statistical information on channel fading. Since it does not require feedback from the destination to the relay nodes, the method is referred to as ”without feedback” below.

Assuming that the link suffers from Rayleigh fading, the link received SNR would satisfy the follow probability distribution function (PDF). For simplicity, the index of the link is dropped.

$$\mathtt{pdf}(\mathtt{SNR} = \rho) = \frac{1}{\rho} e^{-\frac{\rho}{\overline{\mathtt{SNR}}}} \tag{11}$$

where $\overline{\mathtt{SNR}}$ is the average received SNR. A constant value could be chosen to replace $\mathtt{SNR}_{md}$ in the route quality formula.

As for the optimization of this constant value, it is seen in simulations that the overall performance is not sensitive to this value. So it could be set just as 1.

2) With 1-Bit Feedback: In this case, the destination node provides a one-bit feedback to each relay about the relay-destination link quality. This scheme involves three parameters: a fixed threshold value η, known to the destination and all relay nodes; a high representation value η_h, a low representation value η_l, both are known at all relay nodes.

The destination node estimates the received SNR of each relay-destination link, and sends a ”1” to the associated relay node if the received SNR is higher or equal to the threshold η, and a ”0” otherwise. Upon receiving a ”1”, the relay node treats the received SNR equal η_h on its link towards the destination node. A ”0” bit will cause the relay node to approximate the received SNR by η_l. Thus, by only one-bit feedback, the ”approximate” received SNR either by η_h or η_l for the relay-destination link as well as the directed estimated received SNR for the source-relay link are used to estimate the BER for the associated source-relay-destination route.

The three parameter values can be optimized to achieve the best overall performance. It can be seen later in our simulation study that with the optimized values, the proposed scheme can achieve full diversity.

V. Simulation Studies

Simulation studies have been conducted to evaluate the proposed received SNR estimation algorithm and the proposed distributed cooperative routing scheme with the optimized representation of relay-destination link quality at relay node.

A. Estimate Received SNR

In the simulations, it is assumed that the received signals at the relay nodes and the destination node have been pre-processed by the corresponding correlators, and the BPSK data symbols are independently and identically distributed (i.i.d.), while the additive noise is white and circularly rotated complex Gaussian noise with zero mean. The length of the received signal is $K = 1024$ data symbols. The results presented below are obtained by averaging over 10,000 independent runs.

Fig. 2 shows the evaluation results of the proposed received SNR estimation algorithm.

In Fig.2a it is seen that the proposed algorithm provides estimation errors lower than those of the HOS moments-based M2M4 algorithm (see [21]), which is the best existing algorithm with the lowest estimation error. In fact, our estimation errors are very close to the Cramer-Rao bound (CRB) especially at low SNRs. Here we just list two formula of the CRB on the normalized root mean squared (rms) error [19]: one for the case all data symbols are known

$$\mathrm{CRB}(\mathtt{SNR} = \rho) = (2+\rho)\frac{\rho}{K} \tag{12}$$

and one for the case when all BPSK data symbols are unknown

$$\mathrm{CRB}(\mathtt{SNR} = \rho) = \frac{2+\rho\mathtt{f}(2\rho)}{\mathtt{f}(2\rho)+2\rho\mathtt{f}(2\rho)-2\rho}\frac{\rho}{K} \tag{13}$$

where

$$\mathtt{f}(x) = 1 - \frac{e^{-\frac{\rho}{2}}}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} \frac{z^2 e^{-\frac{1}{2}z^2}}{\mathtt{cosh}(\sqrt{\rho} z)} \mathtt{d}z \tag{14}$$

When there are a fraction of data symbols are known, e.g. the training data, the corresponding CRB should be somewhere between these two bounds.

In Fig.2b, it is seen that the proposed algorithm is unbiased over a large range of received SNR from -10 to 20 dB.

B. Represent Relay-Destination Link Quality at Relay Node

In the simulations, it assumed that all links suffer from Rayleigh fading with the same mean value. All the simulation results are obtained by averaging over 1,000,000 independent runs.

Fig. 3 shows the evaluation results when different data forwarding policies are adopted.

For the case without feedback, it can be seen that the overall performance does not exhibit any diversity gain, but still has about ***3dB*** improvements as compared to the random relay route selection. This is easy to understand because although the chosen route unlikely has the best end-to-end route quality among all possible routes, it does have the best source-relay link quality.

For the case with 1-bit feedback, the three parameter values, η, η_h and η_l, are set to be 15, 10 and 5, respectively. It can be

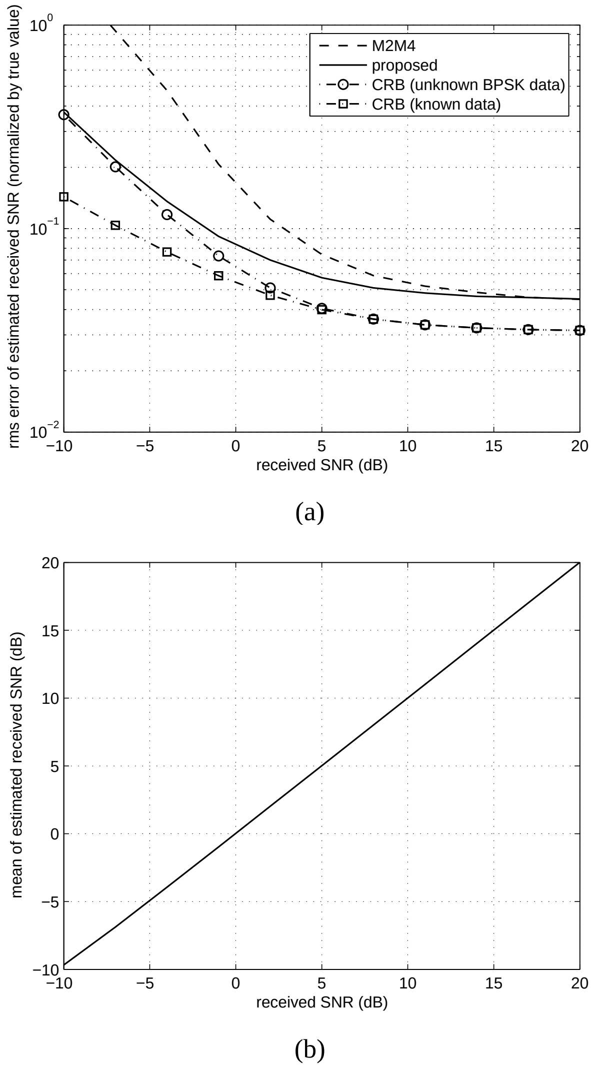

Fig. 2. Proposed estimation algorithm for received SNR: (a) root mean squared (rms) error of the estimated received SNR, normalized by its true value, K=1024; (b) mean of estimated received SNR.

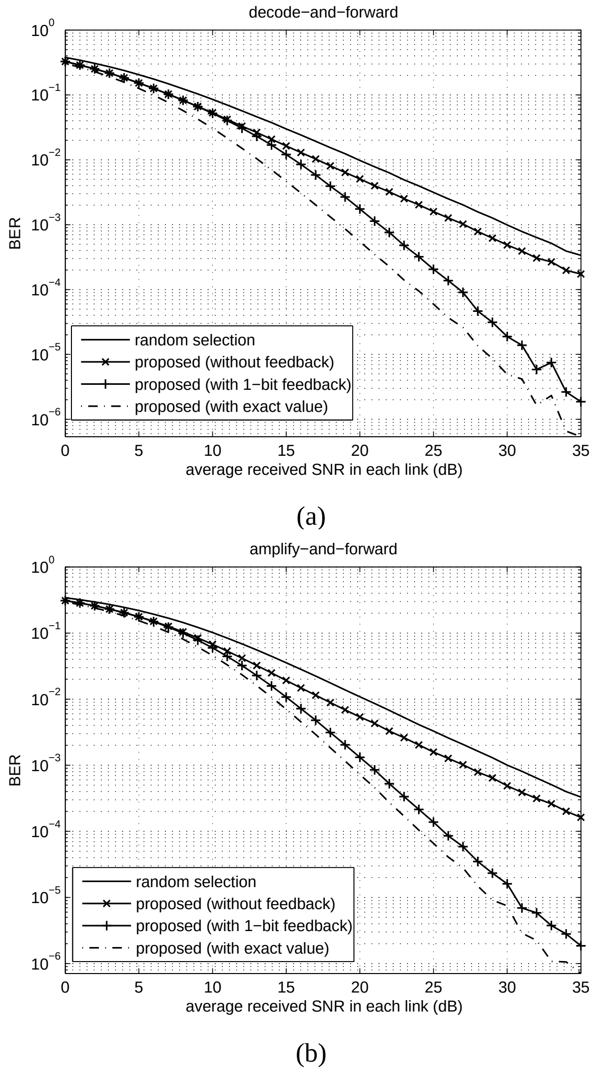

Fig. 3. BER versus average received SNR in each link: (a) decode-and-forward, (b) amplify-and-forward

seen that the proposed scheme can achieve ***full*** diversity, and the overall performance is only ***2dB*** from that with the exact relay-destination link quality. This demonstrates that one-bit feedback is enough for achieving full diversity.

It is also seen that there is no significant difference between the two cases using the two different data forwarding policies: decode-and-forward and amplify-and-forward.

VI. Conclusion

We have proposed a new distributed cooperative routing strategy that forwards data via a multi-hop route with the best, instantaneous quality among available routes in UWB ad-hoc networks. The new method combines the PHY and MAC layer mechanisms to identify the best route in a cooperative and distributed way. We have studied two related issues. First, UWB links using PPM is simplified as *one-dimensional* BPSK data over a complex noise channel. A new, efficient estimation algorithm for received SNR has been presented. The new method is unbiased and its estimation errors are lower than existing algorithms. Second, a distributed cooperative routing scheme has been devised. The new scheme combines the PHY and MAC layer functions to identify the best route in a cooperative and distributed way. Simulation results show that even without any feedback from the destination node to relays and using only statistical characteristics of the link quality, the proposed scheme has a 3 dB improvement in performance as compared to a random route selection. When having 1-bit feedback, the proposed scheme can achieve full diversity and the overall performance is only 2 dB lower than that with true relay-destination link quality. Thus, the proposed distributed cooperative routing is a promising approach to achieve diversity gain, thus enhancing throughput and error performance of wireless ad-hoc networks.

References

[1] C. Siva Ram Murthy and B. S. Manoj, *ad-hoc Wireless Networks: Architectures and Protocols*, Prentice Hall, 2004

[2] UWB Forum webpage, http://www.uwbforum.org

[3] D. Porcino and W. Hirt, ”Ultra wideband radio technology: Potential and challenges ahead”, *IEEE Commun. Mag.*, vol.4, no.7, Jul. 2003

[4] The EU PULSERS research project website, http://www.pulsers.info

[5] The EU PULSERS research project at Imperial College website, http://www.commsp.ee.ic.ac.uk/ wiser/pulsers/

[6] S. R. Aedudodla, S. Vijayakumaran, and T. F. Wong, ”Timing acquisition in ultra-wideband communication systems”, *IEEE Trans. on Vehicular Technology*, vol.54, no.5, Sept. 2005

[7] D. Barras, F. Ellinger, H. Jackel, and W. Hirt, ”A robust front-end architecture for low-power UWB radio transceivers”, *IEEE Trans. on Microwave Theory and Techniques*, vol.54, no.4, Jun. 2006

[8] Tsung-Hui Chang, Chong-Yung Chi, and Yu-Jung Chang, ”Space-time selective RAKE receiver with finger selection strategies for UWB overlay communications”, *IEEE Trans. on Microwave Theory and Techniques*, vol.54, no.4, Jun. 2006

[9] Ning He and C. Tepedelenlioglu, ”Performance analysis of non-coherent UWB receivers at different synchronization levels”, *IEEE Trans. on Wireless Communications*, vol.5, no.6, Jun. 2006

[10] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, ”Cooperative diversity in wireless networks: Efficient protocols and ourage behavior”, *IEEE Trans. Information Theory*, vol.51, no.12, Dec. 2004

[11] K. Azarian, H. E. Gamal, and P. Schniter, ”On the achievable diversity-vs-multiplexing tradeoff in cooperative channels”, *IEEE Trans. Information Theory*, vol.51, no.12, Dec. 2005

[12] Cemal Akcaba, Rohit U. Nabar, and Kin K. Leung, ”A PHY/MAC approach to wireless routing”, *Proc. of IEEE ICC*, 2006

[13] Aggelos Bletsas, Ashish Khisti, David P. Reed, and Andrew Lippman, ”A simple cooperative diversity method based on network path selection”, *IEEE Journal on selected areas of communications*, Vol.24, No.3, 2006

[14] F. Ramirez-Mireles, ”On the performance of ultra wide band signals in Gaussian noise and dense multipath”, *IEEE Trans. VT*, vol.50, no.1, Jan. 2001

[15] L. Zhao and A. M. Haimovich, ”Performance of ultra wide band communications in the presence of interference”, *IEEE J. Sel. Areas Commun.*, vol.20, no.9, Dec. 2002

[16] Sungbin Im and Edward J. Powers, ”An algorithm for estimating signal-to-noise ratio of UWB signals”, *IEEE Trans. VT*, vol.54, no.5, Sept. 2005

[17] David R. Pauluzzi and Norman C. Beaulieu, ”A comparison of SNR estimation techniques for the AWGN channel”, *IEEE Trans. Communications*, vol.48, no.10. Oct. 2000

[18] Norman C. Beaulieu and David R. Pauluzzi, ”comparison of four SNR estimators for QPSK modulations”, *IEEE Communications Letters*, vol.4, no.2, Feb. 2000

[19] Nader S. Alagha, ”Cramer-Rao bounds of SNR estimates for BPSK and QPSK modulated signals”, *IEEE Communications Letters*, vol.5, no.1, Jan. 2001

[20] Bin Li, Robert Di Fazio, and Ariela Zeira, ”A low bias algorithm to estimate negative SNRs in an AWGN channel”, *IEEE Communications Letters*, vol.6, no.11, Nov. 2002

[21] G. Ren, Y. Chang, and H. Zhang, ”A new SNR estimator for QPSK modulations in an AWGN channel”, *IEEE Trans. Circuits and systems II*, vol.52, no.6, Jun. 2005

[22] Ami Wiesel, Jaso Goldberg, and Hagi Messer-Yaron, ”SNR estimation in time-varying fading channels”, *IEEE Trans. Communications*, vol.54, no.5, May 2006