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Resource Utilization Mechanism for Multi-rate Ultra-wide Band Networks

Raed T. Al-Zubi and Marwan Krunz
Department of Electrical and Computer Engineering
The University of Arizona, Tucson, AZ 85721
{alzubi, krunz}@email.arizona.edu

Leo Lopes
• School of Mathematical Sciences
Monash University, Vic 3800, Australia
Leo.Lopes@monash.edu
• Department of Systems and Industrial Engineering
The University of Arizona, Tucson, AZ 85721

Abstract— **Ultra-wideband (UWB) communications has emerged as a burgeoning technology for high data rate wireless personal area networks (WPANs). In this paper, we propose a novel resource utilization mechanism (RUM) for improving the throughput in multi-rate UWB-based WPANs. RUM is intended to remedy a critical issue in both unicast and multicast transmissions. In unicast (single- and multi-hop), the connectivity of a source-destination pair is defined by the ability to overhear control messages (e.g., route requests, request-to-send/clear-to-send, etc.). These messages are usually sent at a low transmission rate to extend their reachability, hence a node can directly communicate with faraway destinations. Such destinations cannot be reliably reached by high transmission rates. This leads to a long channel reservation time and hence a high blocking probability for prospective reservations and low network throughput. In the case of multicast, the maximum transmission rate is bottlenecked by the farthest destination. RUM exploits opportunistic-relaying and time-spreading techniques to improve link reliability and increase the transmission rate, and hence network throughput. Simulations are used to demonstrate the performance gain of RUM.**

I. Introduction

UWB has recently emerged as an attractive technology for short range, high data rate wireless communications. In 2002, the FCC issued the First Report and Order that permitted the deployment of UWB devices [1]. Subsequently, efforts have been made to exploit the unique features of UWB in various contexts, including wireless personal area networks (WPANs), wireless sensor networks, imaging and radar systems, and precision location tracking systems. Several proposals for UWB-based WPANs have been made. One widely popular proposal, which is based on multi-band OFDM, was standardized by the European Computer Manufacturers Association (ECMA) [2]. The standard, called ECMA-368, defines 8 transmission rates (53.3 – 480 Mbps). It uses a TDMA channel access structure, whereby time is divided into 65.536 msec intervals called *superframes* (see Fig. 1). Each superframe is further divided into 256 medium access slots (MASs), grouped into two intervals: a beacon period (BP) and a data transfer period (DTP). The beacon period is used for control and coordination purposes (e.g., bandwidth reservation, synchronization, device discovery). Transmission in the DTP is done using one of two modes: random access and time-based reservation. The latter mode, known as the distributed reservation protocol (DRP), is particularly suitable for real-time streaming between UWB devices. According to DRP, two devices A and B that want to communicate reserve their MASs from the available MASs that are not already reserved by neighboring devices, i.e., those that receive the beaconing frames of A and B. Devices announce their reservation via beacon frames, which are transmitted at the lowest transmission rate (53.3 Mbps). This type of reservation gives devices exclusive access to the medium during the reservation period.

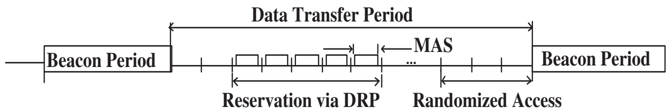

Fig. 1. Superframe structure in ECMA-368.

Recent advances in consumer electronics (CEs) gave rise to dense WPANs and simultaneously high-volume data transfers between CE devices (e.g., video streaming from a DVD to a monitor). One of the critical issues in UWB-based WPANs is how to maintain good throughput in dense topologies. This issue is accentuated in multicast communications, where a target packet delivery probability must be satisfied at all destinations. Hence, the farthest destination limits the operating transmission rate at the sending device. This leads to a long channel reservation time and high blocking probability for prospective reservations, which lowers the network throughput. Even in the case of unicast, two nodes can directly communicate (i.e., single-hop transmission) if they overhear the control messages of each other (e.g., RTS, CTS, beacon frames, etc.). These messages are usually sent at a low transmission rate to extend their reachability, hence a node can communicate with faraway destinations. Such destinations cannot be reliably reached by high transmission rates, hence low network throughput. Novel techniques are needed to increase the link reliability such that high transmission rates can be used while a target packet delivery probability is satisfied.

In an UWB network, the issues of rate adaptation, link reliability, and throughput maximization are all inter-related. To see that, consider the various possible transmission techniques shown in Fig. 2. In this example, suppose that the traffic demand from S to D is 10 Mbps, the packet size is 1 Kbyte, and the required end-to-end packet error rate (PER) is 0.08. In Fig. 2 (a), the source S directly sends data to the destination D at the highest possible transmission rate that satisfies the target PER. The number of required MASs is calculated following ECMA-368 specifications, and is depicted in Fig. 3 as a function of the transmission rate. In Fig. 2 (b), a relay node forwards the data packets to D. This technique results in saving 12

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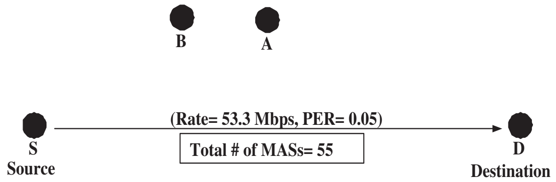
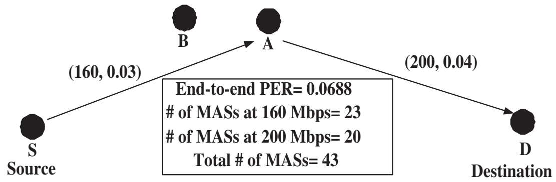
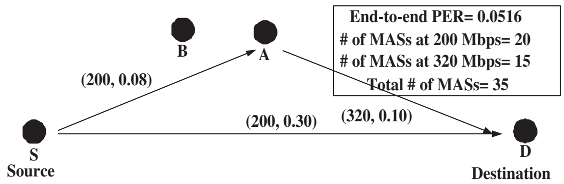


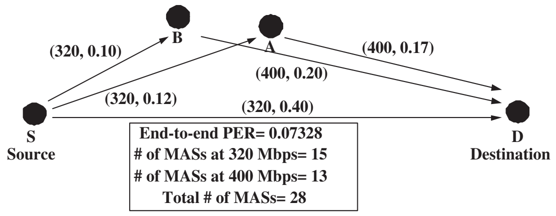
(a) Direct transmission technique



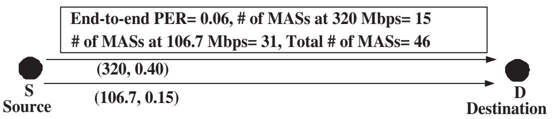
(b) Deterministic relaying technique



(c) Packet overhearing technique



(d) Opportunistic relaying technique



(e) Time spreading technique

Fig. 2. Example illustrates different transmission techniques in UWB network. The parameters between the parentheses represent (transmission rate, PER) of a link.

MASs (relative to the direct transmission) and satisfies the required end-to-end PER. Now, consider Fig. 2 (c). Due to the broadcast nature of wireless communications, device D may overhear some of the transmitted packets from S to A, which if exploited can increase the packet delivery probability. Accordingly, higher transmission rates along the given path can be used, while still satisfying the required end-to-end PER. Relative to the first technique, this technique results in saving 20 MASs and satisfies the required end-to-end PER. It is worth mentioning that this technique was proposed in [3] and [4].

Although the "deterministic relaying" and the "packet overhearing" techniques in Fig. 2 (b) and (c) give some performance gains, we observe that there is room for further improvement. Consider the scheme in Fig. 2 (d). S first broadcasts a data packet to D at a relatively high transmission rate. This packet may be received by D and /or some intermediate nodes. If D does not receive the packet, the closest intermediate node to D that overheard the sent packet relays the packet to D. In this example, A may be such a node. So, A sends its overheard packets that were not received by D. Then, B (the second closest node to D) sends its overheard packets that were not received by A or D. In total, this results in saving 27 MASs. The overall PER under this technique is calculated as follows: PER $= 1 - ((1-0.40) + 0.40(1-0.12)(1-0.17) + 0.40 * 0.12 * (1-0.10)(1-0.20)) = 0.07328\ (< 0.08)$.

It is clear that the performance of the transmission techniques in Fig. 2 (b), (c), and (d) depends on the location of the relay nodes, which is a function of the network topology. To address this limitation, we propose a time-spreading technique that does not depend on relay nodes. In this technique, shown in Fig. 2 (e), the same data packet is sent twice during two consecutive superframes (a detailed discussion of how the transmission process is done is given in Section III). Because the length of a superframe (65.536 msec) is greater than the coherence time of the UWB channel (10 msec [5]), the two transmissions are independent. Therefore, the overall PER in this example is $(0.15)(0.4) = 0.06\ (< 0.08)$ and the required number of MASs is 46, which is less than that in Fig. 2 (a). The main advantage of the time-spreading technique can be illustrated as follows. As we mentioned before, ECMA-368 standard specifies eight transmission rates (i.e., 53.3, 80, 106.7, 160, 200, 320, 400, and 480 Mbps). This finite set of rates restricts the flexibility in rate adaptation. To illustrate, in Fig. 2 (a), sending at 80 Mbps results in PER= $0.1\ (> 0.08)$. In this case, the source must follow a coarse rate-adaptation and use 53.3 Mbps, which requires long channel reservation time. However, use of a time-spreading technique provides nodes with the ability to achieve a PER that is quite close to the target PER. This is equivalent to enabling fine rate adaptation. For example, in Fig. 2 (e), same data packet is sent twice using two transmission rates (106.7 and 320 Mbps). For this example, among all the possible pairs of transmission rates, this pair results in minimum number of MASs and satisfies the target PER. In this example, the time-spreading technique results in 46 MASs (31 MASs at 106.7 Mbps and 15 MASs at 320 Mbps), which correspond to an equivalent transmission rate of 68 Mbps (see Fig. 3).

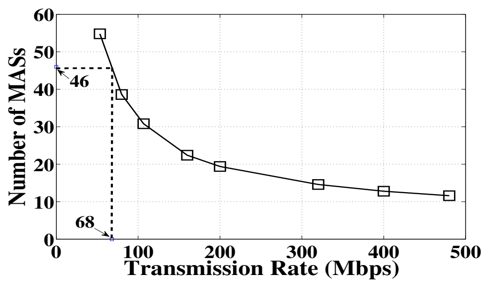


Fig. 3. Number of MASs vs. transmission rate in ECMA-368 [2] (traffic demand = 10 Mbps, packet size = 1 Kbyte).

In this paper, we propose a novel resource utilization mechanism (RUM) for improving the throughput in multi-rate UWB-based WPANs. For each source-destination pair (in unicast or multicast), RUM combines direct transmission, opportunistic relaying, and time-spreading techniques into one mechanism. This combination allows RUM to be adaptive to network topology and to increase the link reliability such that high transmission rate can be reliably used. This leads to short channel reservation time and hence low blocking probability for prospective reservations and high network throughput.

It is worth mentioning that opportunistic relaying has been previously studied in the context of cooperative communications (e.g., [6], [7]). To the best of our knowledge, RUM is the first scheme that improves network throughput by integrating direct transmission, opportunistic relaying, and time-spreading techniques into rate adaptation and slots reservation for unicast

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and multicast transmissions.

The rest of the paper is organized as follows. Section II presents the problem formulation. In Section III, we present the proposed RUM. In Section IV, we use simulations to evaluate the performance of RUM. Finally, our concluding remarks and future work are drawn in Section V.

II. Problem Formulation

Consider an UWB WPAN. The network topology is represented by a graph $\mathcal{G}(\mathcal{N}, \mathcal{L})$, where $\mathcal{N}$ is the set of nodes and $\mathcal{L}$ is the set of links. There is a link $\ell \in \mathcal{L}$ between a pair of nodes if these nodes can communicate directly at the lowest transmission rate (r_1). Given a source node S and a set of destinations $\mathcal{D}$ that are within range of each other (at rate r_1), let the rate demand from S to $\mathcal{D}$ be γ, the PER constraint ε, and the set of transmission rates $\mathcal{R} = \{r_1, r_2, \ldots, r_M\}$. Let $e_\ell(r, \text{SNR}_\ell)$ be the PER over link $\ell \in \mathcal{L}$ when the transmission rate is r and the received SNR is SNR_ℓ. The problem is to select a transmission technique (see Fig. 2) and rate assignment for each transmission such that:

(i) overall end-to-end PER $\leq \varepsilon$ at each destination $\in \mathcal{D}$, and
(ii) total number of time slots is minimized.

In this paper, we use the terms *feasibility condition* and *optimization metric* to refer to (i) and (ii), respectively. Note that in the above formulation, we consider single-hop scenarios. However, as we will see in Section IV, the solution of the above problem can be easily applied to multi-hop scenarios.

III. Resource Utilization Mechanism (RUM)

For a given unicast or multicast transmission, RUM aims at selecting a transmission technique and associated transmission rates that achieve the minimum channel reservation time and that satisfy a target PER. As shown in Fig. 2, the opportunistic relaying technique is a generalized form of the deterministic relaying and packet overhearing techniques. Furthermore, as we will see later, if we also consider the source as a relay node, then the time-spreading technique is a special case of the opportunistic relaying technique. Accordingly, the basic transmission techniques at hand are direct transmission and opportunistic relaying. The performance of these techniques strongly depends on the network topology and the non-linear relationship between PER, SNR, transmission rates, and the number of MASs. For example, if the distance between S and D is very short that it allows the use of the highest transmission rate (r_M), then direct transmission is clearly the best choice. To make RUM adaptive to network topology, RUM tests both basic techniques (i.e., direct and opportunistic relaying), and then selects the one that requires fewer MASs while satisfying the target PER. As we will see later, the testing process incurs reasonable computational overhead. For direct transmission, the maximum possible transmission rate is easily selected based on the channel gain (i.e., SNR). However, in opportunistic relaying, the selection process is not simple and can be explained as follows.

Generally, opportunistic relaying (including the time-spreading technique as a special case), involves three steps. First, the source S selects a pair of transmission rates: one is used to send data packets from the source, and the other is used to forward the overheard packets by the relay nodes. Note that all the relay nodes use the same transmission rate. This helps S to compute the required channel time that should be reserved for packet relaying. Second, the source selects a set of relaying nodes. Third, the source determines a packet relaying schedule. As we will see later, these steps are inter-related. Therefore, for each pair of transmission rates (for M rates, there are M^2 pairs), S selects a set of relay nodes and a relaying schedule. The source chooses the pair of transmission rates and the corresponding relay nodes and relaying schedule that result in minimum number of MASs and at the same time satisfy the target end-to-end PER. To explain these steps in more detail, we consider the case of multicast transmission (unicast is a special case of multicast).

In a multicast transmission, there are multiple destinations per source, and the target PER should be satisfied at each destination. Consider the example in Fig. 4. In this example, data packets sent from S to a set of destinations $\mathcal{D} = \{D_1, D_2\}$. The source S cooperates with a set of intermediate nodes ψ (selected by S) to forward packets to the destinations in $\mathcal{D}$. To simplify the cooperation process, ψ is selected such that all the members of this set are neighbors of each other (i.e., they can hear the beacons of each other). For a given pair of transmission rates, the selection of ψ is performed as follows.

- S selects the set of nodes Ψ that are neighbors of S and all $D_i \in \mathcal{D}$. In Fig. 4, $\Psi = \{N_1, N_2, N_4, S\}$. Note that S can itself serve as a relay node. In this case, opportunistic relaying embodies the time-spreading technique.
- S computes the end-to-end PERs over the paths from S to each $D_i \in \mathcal{D}$ through each node in Ψ. For example, in Fig. 4, for each intermediate node in Ψ, two values of PERs are calculated. To illustrate, for N_2, end-to-end PERs are calculated over: $S \to N_2 \to D_1$ and $S \to N_2 \to D_2$ (let PER* be the maximum of these two values).
- S sorts the nodes in Ψ from best to worst, according to the values of PER*. For example, in Fig. 4, the sorted list is $\Psi = \{N_2, N_4, N_1, S\}$. Note that the first node in the sorted list has the minimum worst end-to-end PER (minimum PER*).
- S sequentially examines each member in the sorted list, starting from the best one. If the member is not a neighbor of all previous members in the list, it is removed from the list. The remaining set of nodes in Ψ represents the set ψ (i.e., $\psi \subseteq \Psi$). To illustrate, consider the sorted list $\Psi = \{N_2, N_4, N_1, S\}$. N_4 is a neighbor of N_2, hence it stays in the list. Now, assume N_1 is not a neighbor of N_4, then it is removed from the list. Therefore, for this example, $\psi = \{N_2, N_4, S\}$. Note that if $\psi = \{S\}$, then the opportunistic relaying is reduced to the time-spreading technique.

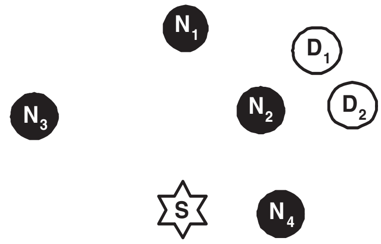


Fig. 4. Example that illustrates opportunistic relaying for a multicast transmission from S to two destinations (D_1 and D_2). Based on the distances between the relay nodes and the destinations, the best relaying schedule is N_2, N_4, then S.

After selecting ψ, the relaying schedule is computed, as follows. Suppose that the channel gains between a given relay node and all the destinations in $\mathcal{D}$ are available. Among these values, denote the smallest (worst) value by G_o. Now, assume that a packet sent by S is received by all the relay nodes in

ψ. Then, the node in ψ that should relay the received packet is the one that has the maximum G_o. S determines the relaying schedule based on the values of G_o.

To illustrate, consider Fig. 4, with based on the distances (which approximately represent channel gains or SNR) between the relay nodes and the destinations, the best relaying schedule is N_2, N_4, then S. Based on the selected relaying schedule, the overall end-to-end PER to each destination is calculated.

The above steps are done for each pair of transmission rates. In total, there are M^2 different pairs. A pair is said to be feasible if the target PER at each destination in $\mathcal{D}$ is satisfied. Among all feasible pairs of transmission rates, S selects the one that requires the minimum number of MASs. The corresponding relay nodes and relaying schedule are adopted. A pseudo-code of RUM for multicast and unicast transmissions is shown in Algorithm 1.

Algorithm 1 RUM for multicast and unicast transmissions (executed at the source)

Input: $\mathcal{G}(\mathcal{N},\mathcal{L})$, $\mathcal{R}=\{r_1,r_2,\ldots,r_M\}$, ε, S, $\mathcal{D}$
$n(r)$ % number of MASs at rate r, $e_\ell(r,\text{SNR}_\ell)$
for all $\ell\in\mathcal{L}$ and $r\in\mathcal{R}$
Output: The best (in terms of number of MASs) feasible pair of transmission rates (r_a,r_b) and relaying schedule (R_s^*)
Initialization: $n_o=\infty$ % minimum number of required MASs
• Select Ψ
for all $r_i\in\mathcal{R}$ % r_i: rate used by S
for all $r_j\in\mathcal{R}$ % r_j: rate used by relay nodes
{
• for each $N_i\in\Psi$, compute end-to-end PER over $S\rightarrow N_i\rightarrow\forall D_i\in\mathcal{D}$
• Sort nodes in Ψ according to the worst end-to-end PER
for all $N_i\in$ sorted Ψ (starting from the best)
if N_i is not a neighbor for all previous nodes in the sorted Ψ, then remove N_i from Ψ (the rest of Ψ represents ψ)
• Determine the relaying schedule (R_s) by sorting ψ according to the channel gain between each $N_i\in\psi$ and all $D_i\in\mathcal{D}$
• Compute the end-to-end PER between S and D_i, $\forall D_i\in\mathcal{D}$ based on r_i, r_j, and R_s
if (all end-to-end PER values $\leq\varepsilon$) and $(n(r_i)+n(r_j)<n_o)$
$r_a=r_i,\quad r_b=r_j,\quad n_o=n(r_i)+n(r_j),\quad R_s^*=R_s$
}

Complexity: In the multicast case, the worst-case computational complexity of RUM is $\mathcal{O}(|\mathcal{N}|^2M^2+|\mathcal{N}|)$. To see that, note that Ψ is selected with computational complexity of $\mathcal{O}(|\mathcal{N}|)$, and for each pair of transmission rates, ψ and the relaying schedule are selected with computational complexity of $\mathcal{O}(|\mathcal{N}|^2)$ (assuming a typical sorting algorithm is used with complexity of $\mathcal{O}(|\mathcal{N}|^2)$).

Example: We illustrate the operation of RUM through a simple unicast example. In Fig. 5, S has packets to send to D. It sends ten packets during a given superframe. Some of these packets are correctly received by the destination D and/or relay nodes A and B, as shown in Fig. 5. In the next superframe, nodes D, A, and B announce the received packets using their beacon frames. Let the relaying schedule (discussed before) for the intermediate nodes be A then B. Therefore, A starts sending its received packets that are not received by D (packets 1, 3, and 7). Then, B sends its overheard packets that were not received by A or D (packets 2, 4, 8, and 10). Finally, S resends the packets that were not received by D or any intermediate node (packet 9). Note that S is considered as a relay node.

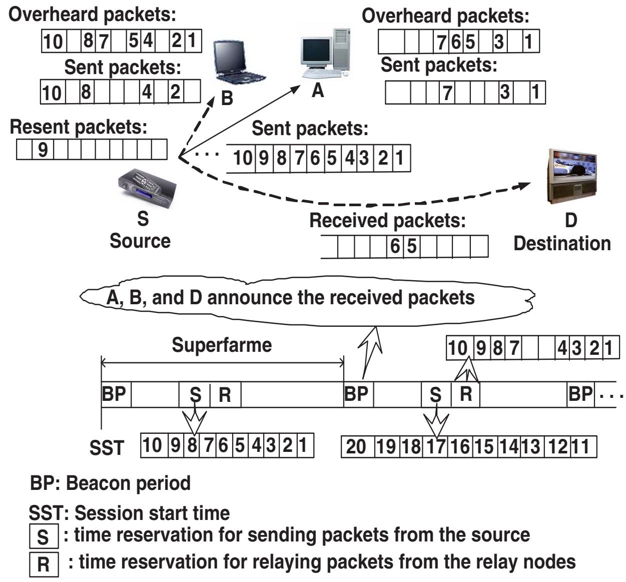


Fig. 5. Example that illustrates the operation of RUM for unicast transmission.

IV. Performance Evaluation

A. Simulation Setup

We study the performance of RUM in unicast (single-hop and multi-hop) and multicast scenarios. Our results are based on simulation experiments conducted using CSIM (a C-based process-oriented discrete-event simulation package [8]). The determination of interference and noise is done according to a physical (SINR) model. We consider an UWB network, where N nodes are randomly placed in a square of length L (in meters). In the unicast case, nodes are randomly paired. For the multicast case, different sources with different number of destinations per source are randomly selected. For simplicity, data packets are assumed to have a fixed size (1 KB). Other parameter values used in the simulation are given in Table I. These values correspond to realistic hardware settings that were used in related studies (e.g., [9]).

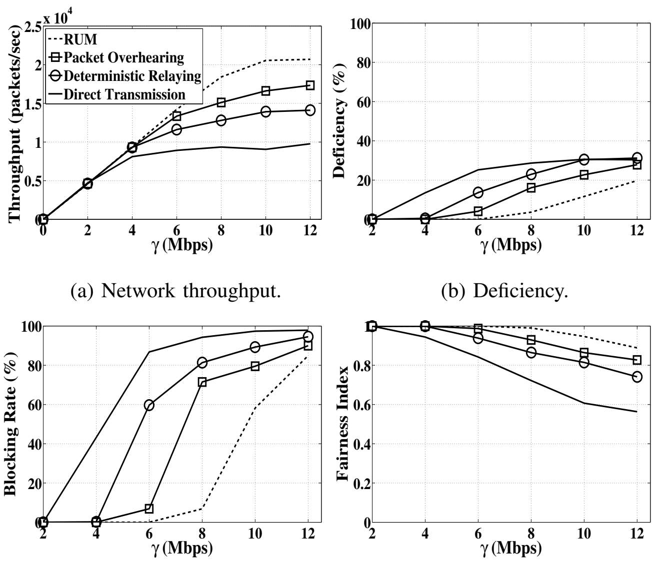
Transmission rates	53.3-480 Mbps
Average transmission power	-10.3 dBm
Transmitter antenna gain	0 dBi
Receiver antenna gain	0 dBi
Path loss factor	2
Receiver noise figure	6.6 dB
Hardware-related loss	2.5 dB

TABLE I
Parameters used in the simulation.

B. Results

We mainly focus on four performance metrics: (1) network throughput (i.e., goodput), (2) Jain's fairness index (i.e., throughput fairness) (3) blocking rate, and (4) *deficiency*. Before explaining these metrics, we first clarify the procedure for establishing a session between two nodes. A source node starts by checking the available channel time, i.e., unreserved MASs in the superframe. We assume elastic traffic. For this type of traffic, the session can be established using whatever channel time is available (but not to exceed the required demand), and the unsatisfied load is captured via the deficiency metric. If there is no any available channel time, the request will be blocked. Accordingly, we calculate the deficiency as the ratio between the unsatisfied load and the total offered load. We also calculate the blocking rate as the ratio between the number of blocked sessions and the total number of generated sessions.

Fig. 6 depicts the various performance metrics versus the traffic load γ for a single-hop scenario (i.e., any source-destination pair can communicate directly at rate r_1). In this figure, we contrast the performance of RUM with the transmission techniques shown in Fig. 2 (a), (b), and (c). For the packet overhearing and deterministic relaying techniques, we use exhaustive search to select the optimal relay node and the transmission rates. As shown in this figure, the results are in line with the example given in Fig. 2. RUM achieves the best performance with respect to all performance metrics. RUM achieves a significant throughput improvement (up to 111%, 54%, and 26% relative to the direct transmission, deterministic relaying, and packet overhearing techniques, respectively).



(a) Network throughput. (b) Deficiency.

(c) Blocking rate. (d) Throughput fairness.

Fig. 6. Performance of various transmission techniques versus traffic load γ under unicast (single-hop) transmissions ($N = 20$, Area = 20 x 20 m^2).

Next, we study the effect of integrating RUM into the Ad hoc On-Demand Distance Vector (AODV) routing protocol for multi-hop communications (using the min-hop metric for route selection). In this experiment, RUM is used to select the best transmission technique and transmission rates over each link of the path provided by AODV. As shown in Fig. 7, RUM improves the network throughput up to 109%. This result is in line with the results in Fig. 6.

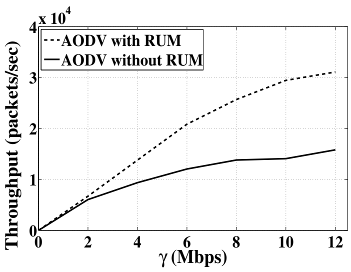


Fig. 7. Throughput performance of AODV with/without RUM ($N = 30$, Area = 30 x 30 m^2).

Finally, in Fig. 8, we study the performance of RUM for multicast transmissions. In this experiment, the source can directly communicate with all its destinations at the lowest transmission rate (r_1). Note that, as mentioned before, the number of destinations per source is randomly selected. Fig. 8 shows that RUM achieves a high throughput improvement (up to 43%). The result shown in Fig. 8 supports the trends in Figs. 6 and 7.

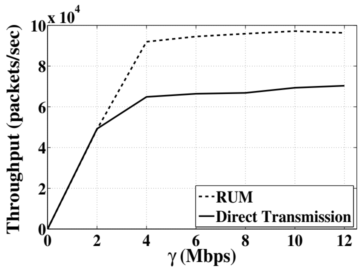


Fig. 8. Throughput performance of RUM for multicast communications ($N = 20$, Area = 20 x 20 m^2).

V. Conclusions and Future Work

In this paper, we proposed a resource utilization mechanism (RUM) for improving the throughput of a multi-rate UWB-based WPAN. For each source-destination pair, RUM exploits opportunistic relaying and time-spreading techniques to increase the link reliability such that high transmission rate can be used while at the same time a target end-to-end PER is satisfied. We compared the performance of RUM with that of other transmission techniques. Our simulation results showed that RUM improves the network throughput (up to 111%, 109%, and 43% in unicast (single-hop), unicast (multi-hop), and multicast communications, respectively). For our future work, we will use the time-spreading technique to control the transmission power and increase the spatial reuse of the medium. In this case, a packet is sent twice using a low transmission power while satisfying a target PER. This technique results in reserving the medium over a small area for a long time by one source-destination pair. However, at the same time, it allows many reservations to be established over adjacent areas.

References

[1] *First Report and Order: In the Matter of Revision of Part 15 of the Commissions Rules Regarding Ultra-Wideband Transmission Systems*, FCC, FCC 02-48, April 2002.

[2] *ECMA-368 (3rd Edition): High Rate Wideband PHY and MAC Standard*, European Computer Manufacturers Association (ECMA), December 2008.

[3] R. Al-Zubi and M. Krunz, "Overhearing-aware joint routing and rate selection in multi-rate UWB-based WPANs," *accepted for the IEEE INFOCOM Conference*, 2010.

[4] ——, "Cross-layer design for efficient resource utilization in WiMedia UWB-based WPANs," *to appear in the ACM Transactions on Modeling and Computer Simulation (TOMACS)*.

[5] E. Masazade, M. Keskinoz, and O. Gurbuz, "Proportional time sharing with frame size adaptation for MB-OFDM based UWB WPANs," in *Proceedings of the IEEE Systems, Applications, and Technology Conference, IEEE Long Island (LISAT)*, 2006.

[6] S. Biswas and R. Morris, "ExOR: Opportunistic multi-hop routing for wireless networks," in *Proceedings of the ACM Annual Conference of the Special Interest Group on Data Communication (SIGCOMM)*, August 2005.

[7] H. DuboisFerri, D. Estrin, and M. Vetterli, "Packet combining in sensor networks," in *Proceedings of the ACM Conference on Embedded Networked Sensor Systems (SenSys)*, November 2005.

[8] Mesquite Software Incorporation, http://www.mesquite.com.

[9] A. Batra, J. Balakrishnan, G. R. Aiello, J. R. Foester, and A. Dabak, "Design of a multiband OFDM system for realistic UWB channel environments," *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 9, September 2004.