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IMPORTANT: Integrating Multi-rate caPability into Opportunistic Routing in uwb-based Ad hoc NeTworks ☆

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ABSTRACT

Ultra-wideband (UWB) communications has emerged as a burgeoning technology for high data rate wireless personal area networks (WPANs). In this paper, we exploit the integration of rate assignment into opportunistic routing under a required QoS, i.e., end-to-end packet error rate (PER), for improving the performance of UWB-based WPANs. Opportunistic routing has been proposed for ad hoc networks. In this type of routing protocols, instead of determining a static path ahead of time, the path is constructed dynamically. The protocol exploits the broadcast nature of wireless communications by allowing packet forwarding to be done by the closest recipient to the destination. Several works showed that opportunistic routing improves network performance. None of these works studied the integration of rate assignment into opportunistic routing while satisfying a target QoS. In this paper, we formulate and study this integration. In our setup, we aim at determining the required number of retransmissions in opportunistic routing and the transmission rate in each retransmission such that the required delivering time for a sent packet is minimized while at the same time a certain end-to-end PER is satisfied. We show that this problem is NP-hard. Accordingly, we propose an approximate solution called IMPORTANT. Extensive simulations over a UWB-based WPAN show that IMPORTANT achieves high performance relative to different techniques (21–48% throughput improvement).

1. Introduction

UWB has recently emerged as an attractive technology for short range, high data rate wireless communications (i.e., WPANs). Recent advances in consumer electronics (CEs) gave rise to dense WPANs (i.e., more CEs in people's living rooms) and simultaneously high-volume data transfers between CE devices (e.g., video streaming from a DVD to a monitor). One of the requirements that impact the future growth of UWB-based WPANs is mitigating throughput starvation in such dense topologies while satisfying a specific QoS requirement (end-to-end PER is considered in this paper). Several techniques that proposed for wireless communications can be employed to improve the performance of UWB-based WPANs. One of these techniques is to exploit the broadcast nature inherent of wireless medium by allowing the nodes to cooperate in order to achieve robust packet forwarding and hence reducing the time required for packet retransmission. Exploiting node cooperation has received significant attention (e.g., [1–6]). Recently, a new cooperation-based routing paradigm called opportunistic routing emerged as a viable approach for reliable transmission in wireless communications. In this routing paradigm, the routing decisions are made opportunistically, where the next forwarding relay of a transmitted packet is selected based on the outcome of the previous transmission (i.e., the next relay is the closest packet recipient to the destination). Several opportunistic routing protocols (e.g., [5,7–9]) showed a significant improvement in the overall network performance. Another mechanism that is employed to improve the performance of wireless communications is to provide devices with multi-rate capability. Several wireless networking standards support this capability (e.g., IEEE 802.11a/b/g standards, ECMA-368 standard for OFDM-based UWB [10], etc.). This capability allows nodes to cope with the dynamic nature of the wireless medium by adjusting the transmission rate according to channel conditions. The transmission rate of a packet is directly related to its transmission time and the packet error rate (PER); the higher the

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transmission rate, the smaller the transmission time but the higher the PER, which impacts the overall network throughput. Therefore, a well-designed rate selection mechanism must achieve the optimal balance between these parameters. As an example, in [11], the authors showed that sending a packet twice at high transmission rates while satisfying a target PER incurs less time than sending the same packet once using a low transmission rate and while satisfying the same target PER.

1.1. Motivation

It is worth mentioning that the rate adaptation and opportunistic routing are inter-related. To illustrate, consider the example in Fig. 1. In this example, assume opportunistic routing is applied and all nodes have a multi-rate capability. If the source sends a packet using a low transmission rate, then there is a high probability that node *B* will receive the packet and relay it (since node *B* is the closest packet recipient to the destination). Hence, there is a high probability that one relay is required in this case. However, if the source uses a high transmission rate, then there is a high probability that node *A* will be the only receiver of the sent packet. If node *A* relays the packet using a high transmission rate, then there is a high possibility that node *B* will be the next receiver. Therefore, in this case, the expected number of relays is two. It should be noted that in this example, we discussed only two possible scenarios. The best of them is the one that minimizes the total delivering time and simultaneously satisfies a target end-to-end PER. It turns out that finding the best possible route is not easy since the number of cases increases exponentially with the number of relay nodes, not to mention that the relationship between the transmission rate, PER, and transmission time is nonlinear (as explained later in Section 6.1).

1.2. Contributions

A small number of researchers considered the problem of integrating rate adaptation into opportunistic routing. In recent works [12–14], the authors study the capacity of opportunistic routing in multirate and multihop wireless network. However, they do not consider satisfying a QoS requirement in their study. In this paper, to improve the performance of UWB-based WPANs, we formulate and study the integration of multi-rate capability into opportunistic routing while satisfying a target end-to-end PER (PER is an important quality of service parameters for wireless network [15]). Specifically, we consider the problem of determining the number of (re)transmissions n that are required to deliver a packet to its destination (via opportunistic routing) and the rate assignment per (re)transmission such that the expected total time for all (re)transmissions is minimized while at the same time a target end-to-end PER is satisfied. Note that the first transmission is done by the source node and the subsequent $n-1$ retransmissions are done by relay nodes (each retransmission is done by the closest packet recipient to the destination). We show that this problem is NP-hard. Accordingly, we propose an approximate solution called IMPORTANT (Integration of Multirate caPability into Opportunistic RouTing in uwb-based Ad hoc NeTwork). The basic idea behind IMPORTANT is that the source node calculates the maximum possible number of (re)transmissions ($n_{\max}$), assuming that the source itself will perform each transmission using the maximum transmission rate for each, i.e., the maximum PER will be considered in each (re)transmission. Then, for each possible number of (re)transmissions n ($1 \leqslant n \leqslant n_{\max}$), the source employs a proposed rate assignment algorithm to find the best combination of transmission rates that minimizes the expected delivering time and satisfies the target PER. Finally, the source determines the best number of (re)transmissions n and the associated rate assignment that result in minimum channel-time and that satisfy the target PER.

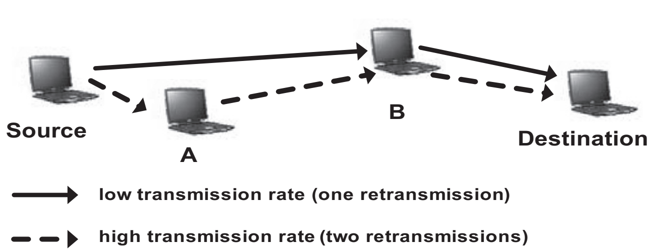


Fig. 1. Example illustrates the inter-dependence between opportunistic routing and rate adaptation.

Using simulations, we show the effect of IMPORTANT on the overall performance of a WiMedia OFDM-based multi-hop, multi-rate UWB network [10]. It is observed that IMPORTANT achieves 21–48% throughput improvement compared with the routing techniques in [5,16–18].

1.3. Organization

The rest of the paper is organized as follows. In Section 2, we present related work. Section 3 overviews WiMedia OFDM-based UWB. The problem setup and formulation are provided in Section 4. Section 5 presents our proposed IMPORTANT scheme. In Section 6, we use simulations to evaluate the performance of IMPORTANT. Finally, our concluding remarks are drawn in Section 7.

2. Related work

Several works (e.g., [5,19–21,16,17,11]) have been proposed to exploit packet overhearing and spatial diversity in wireless communications, and cope with unreliable transmissions. The authors in [5] exploited packet overhearing to improve the performance of an opportunistic routing protocol. According to this protocol, one of the nodes that overheard the transmitted packet is chosen to forward the packet. For a set of packets, the source selects a list of forwarding nodes. The selection of this list is done based on the forward delivery probability. The work in [19] is based on the fact that even when no node receives (overhears) a whole packet correctly, any given bit is likely to be received (i.e., overheard) correctly by some nodes. Nodes that overhear a transmitted packet are allowed to forward parts of this packet, allowing the final destination to recover the original packet. In [20], packet overhearing was employed to reduce the overhead of route discovery, where routing information may be obtained in advance by analyzing overheard packets. In [21], the authors proposed a packet combining mechanism, which exploits spatial diversity by using overheard packets at any node. The nodes buffer corrupted packets, and when two or more corrupted packets are received, the packet combining procedure attempts to recover the original packet from the corrupted versions. None of the aforementioned works takes the advantage of integrating the multi-rate capability (which is supported by most of the wireless communications standards) into the opportunistic forwarding paradigm. In recent works [12–14], the authors theoretically study the end-to-end throughput (i.e., capacity) of opportunistic routing in multirate and multihop wireless network. They validate the analysis results by simulation, and show that opportunistic routing has great potential to improve end-to-end throughput and system operating at multi-rates achieves higher throughput than that operating at any single rate. Unlike our work in this paper, the authors in [12–14] do not consider satisfying a target QoS requirement in the integration of rate assignment into opportunistic routing. It is clear that considering a specific QoS requirement increases the complexity of the problem. In [16,17], the authors proposed an overhearing-aware joint routing and rate selection scheme. For a given source–destination pair, this scheme aims at selecting a path (not an opportunistic path) and the transmission rates over this path that achieve the minimum reservation time, leading to low blocking rate for prospective reservations and high network throughput. In [11], the authors proposed an opportunistic relaying mechanism for a single-hop network. In this mechanism, only one retransmission is allowed for each non-received packet. The retransmission is done by the closest packet recipient to the destination. The transmission and retransmission rates are selected by the source node such that the total reserved channel time is minimized while a target end-to-end PER is satisfied.

3. WiMedia OFDM-based UWB

In 2002, the FCC issued the first report and order that permitted the deployment of UWB devices [22]. Subsequently, efforts have been made to exploit the interesting features of UWB for various applications, 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 is the multi-band OFDM-based UWB system. Industry advocates of this system formed an organization called the Multi-band OFDM Alliance (MBOA) [23], which eventually evolved into a large industrial alliance known as the WiMedia alliance. WiMedia defines, certifies, and supports enabling wireless technology for multimedia applications. Its UWB specifications have been adopted by the European Computer Manufacturers Association (ECMA) as a basis for a OFDM-based UWB standard [10]. The standardized OFDM-based UWB system called (ECMA-368) defines 8 data rates (53.3–480 Mbps). According to this standard, time is divided into 65.536 msec periodic intervals, called *superframes* (see Fig. 2 [10]). Each superframe is further divided into 256 medium access slots (MASs). The superframe consists of two parts: 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 can use two modes of reservations: random access and time-based reservations. The latter mode, known as the distributed reservation protocol (DRP), is particularly suitable for real-time (voice and video) traffic between UWB devices. According to DRP, devices that want to communicate with each other reserve their required MASs from the available MASs that are not reserved by their neighbors.

4. Problem setup and formulation

4.1. Problem setup

We consider a mobile ad hoc network, whose 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. A link ℓ exists between two nodes if these nodes can communicate directly at the lowest transmission rate r_1 while satisfying a target end-to-end packet error rate (ε). Each node in $\mathcal{N}$ is provided with a set of transmission rates $\mathcal{R} = \{r_{(1)}, r_{(2)}, \ldots, r_{(M)}\}$, where $M = |\mathcal{R}|$ and $r_{(1)} \leqslant r_{(2)} \leqslant \ldots \leqslant r_{(M)}$. Each link $\ell \in \mathcal{L}$ is associated with two sets of parameters:

- $t_\ell(r_i)$: transmission time that is required to send a packet over link ℓ by a node i at a transmission rate $r_i, \forall r_i \in \mathcal{R}$.
- $e_\ell(r_i, \mathrm{SNR}_\ell)$: PER over link ℓ when this link is operated at a transmission rate r_i and the received SNR is $\mathrm{SNR}_\ell, \forall r_i \in \mathcal{R}$.

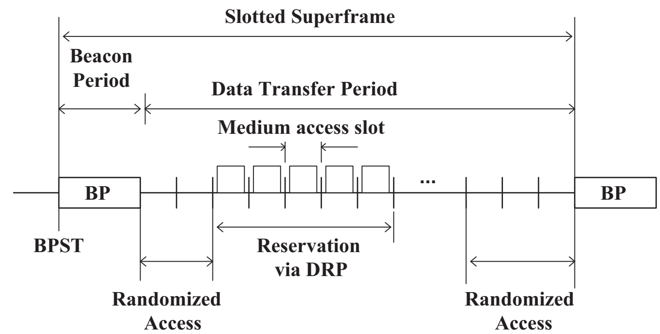


Fig. 2. Superframe structure in ECMA-368.

In our problem, a packet that is sent from a source $S \in \mathcal{N}$ is opportunistically forwarded to its destination $D \in \mathcal{N}$ through a number of relay nodes. To illustrate the packet forwarding process, consider the simple example in Fig. 3. In this example, $P_{ij}(r_i)$ is the probability of receiving a packet sent from node i to node j at a transmission rate $r_i \in \mathcal{R}$. Before explaining this example, it is worth mentioning that the detailed discussion of the practical implementation of opportunistic routing will be explained in Section 5. In this example, the source (node 0) first transmits a data packet at a given transmission rate $r_0 \in \mathcal{R}$. If the destination does not receive this packet, then the closest recipient relative to the destination retransmits the data packet (assume this is node 1 in the example). After that, if the destination still does not receive the data packet from node 1, then a second retransmission is done by the closest packet recipient. Assume that node 2 successfully received the data packet from node 1 after the first retransmission. Then, node 2 will be the one that performs the second retransmission. Note that in this example if both nodes 1 and 2 do not receive the first transmission, then the source node will perform the retransmission process.

It is known that the higher the link transmission rate, the smaller the transmission time of the packet, and hence the higher the number of other prospective transmissions (i.e., higher network throughput). At the same time, the transmission rate also impacts the PER over a link; for a given link quality (i.e., SNR), the higher the transmission rate, the higher the PER, and hence the higher the number of required retransmissions. This places an upper limit on the transmission rate that can be used to support a target PER. Accordingly, in opportunistic forwarding, the rate assignment (i.e., selecting $r \in \mathcal{R}$) for each (re)transmission attempt over a link $\ell \in \mathcal{L}$ affects the required number of retransmissions, the end-to-end PER, and the overall throughput. In our problem, the number of retransmissions by all the relay nodes and the rate assignment per retransmission are to be determined by the source node such that the expected transmission time (i.e., number of MASs in an UWB network) for all retransmissions is minimized while at the same time a target end-to-end PER is satisfied.

4.2. Problem formulation

To formulate the aforementioned problem, we model the opportunistic routing process between a source and its destination

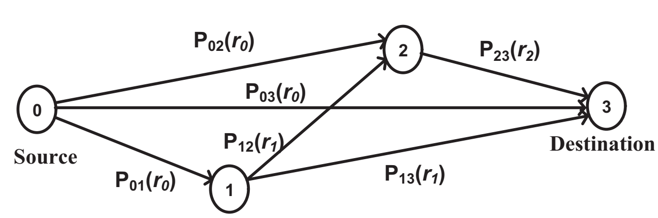


Fig. 3. Example that illustrates opportunistic forwarding.

Table 1
Possible system states after any packet (re)transmission for the example shown in Fig. 3

Node	Possible states				
	S_0	S_1	S_2	S_3	S_4
1	0	1	0	1	0/1
2	0	0	1	1	0/1
3	0	0	0	0	1

as an absorbing Markov chain. We denote any possible state of the system after each (re)transmission process by $S_x = \{s_1, s_2, \ldots, s_{nr+1}\}$, where $nr+1$ is the number of relay nodes (including the destination) between the source and its destination, $x \in \{0, 1, \ldots, 2^{nr}\}$, and $s_i \in \{0, 1\}$; $s_i = 1$ means that node i has a copy of the packet after the (re)transmission process and $s_i = 0$ means otherwise. For the sake of illustration, Table 1 shows all the possible states for the example in Fig. 3. In this table, “1” means that the node received the sent packet, and “0” means otherwise. For our UWB-based network, it is clear that, for each (re)transmission process, the sender node reserves a number of MASs and (re)sends the packets during the reserved MASs using a certain data rate $r \in \mathcal{R}$. After that, the system moves from one possible state to another possible state (or stays in the same state), as shown in Fig. 4 (this figure will be shortly explained in more detail). The transition from one state to another depends on the used transmission rate, which determines the probability of receiving a sent packet by other nodes. The transition process will be terminated once the sent packet from the original source is received by the final destination (state S_4) in Table 1). We model this system as an absorbing Markov chain as follows. All the possible states of the system after each (re)transmission process represent the states of the Markov chain. This chain reaches its absorbing state once it reaches a state where the packet is received by the destination. The transition probabilities between these states are functions of the used transmission rate in each (re)transmission process.

As will be discussed shortly, modeling our system as an absorbing Markov chain allows us to find the expected number of retransmissions required to reach the absorbing state and the probability that the system is in a certain state after n retransmissions. In fact, by using these results, we can calculate the expected total number of MASs required to transmit a packet from the source to its destination. Note that the number of MASs in each (re)transmissions, the expected number of retransmission, and the packet error rate are functions of the used transmission rates. Accordingly, we can formulate our problem as an optimization problem, in which we try to find the best rate assignment for the retransmission processes that results in the minimum number of MASs required to deliver a packet from a source to its destination while meeting a target end-to-end PER. In this optimization problem, the expected number of (re)transmissions is an indirect decision variable. In the following subsections, we illustrate how the absorbing Markov chain is used to find the expected number of (re)transmissions and how the optimization problem is formulated.

4.2.1. Expected absorbing time

Recall that in a Markov chain if there are b absorbing states and z transient states, the transition matrix $\mathbf{A}$ will have the following canonical form

$$\mathbf{A} = \begin{pmatrix} \mathbf{Q} & \mathbf{R} \\ \mathbf{0} & \mathbf{I} \end{pmatrix} \tag{1}$$

where $\mathbf{I}$ is a b-by-b identity matrix, $\mathbf{0}$ is a b-by-z zero matrix, $\mathbf{R}$ is a nonzero z-by-b matrix, and $\mathbf{Q}$ is a z-by-z matrix.

To find the expected absorbing time of the Markov chain (i.e., the expected number of retransmissions in our problem), we employ the following known property [24]:

Property 1. *Let m_i be the expected number of steps before the chain is absorbed, given that the chain starts in state S_i, and let $\mathbf{m}$ be a column vector whose ith entry is m_i. Then $\mathbf{m} = \mathbf{Fc}$, where $\mathbf{c}$ is a column vector whose entries are 1 and $\mathbf{F} = (\mathbf{I} - \mathbf{Q})^{-1}$ is the so-called fundamental matrix for the Markov chain.*

For the sake of illustration, consider the example shown in Fig. 3. This example can be modeled as a five-state absorbing Markov chain. These states are shown in Table 1. In this table, “1” means that the node received the sent packet, and “0” means otherwise. To construct the transition probability matrix, we consider two facts. First, it is impossible to move from state “1” to state “0”; if a node receives a packet, it will keep a copy of it until all retransmissions are done. Second, the Markov chain reaches the absorbing state (S_4) once the destination receives the sent packet. Based on these facts, the transition probability matrix $\mathbf{A}$ can be written as follows:

$$\mathbf{A} = \begin{bmatrix} \overline{P_{01}(r_0)}\,\overline{P_{02}(r_0)}\,\overline{P_{03}(r_0)} & P_{01}(r_0)\,\overline{P_{02}(r_0)}\,\overline{P_{03}(r_0)} & \overline{P_{01}(r_0)}\,P_{02}(r_0)\,\overline{P_{03}(r_0)} & P_{01}(r_0)\,P_{02}(r_0)\,\overline{P_{03}(r_0)} & P_{03}(r_0) \\ 0 & \overline{P_{12}(r_1)}\,\overline{P_{13}(r_1)} & 0 & P_{12}(r_1)\,\overline{P_{13}(r_1)} & P_{13}(r_1) \\ 0 & 0 & \overline{P_{21}(r_2)}\,\overline{P_{23}(r_2)} & P_{21}(r_2)\,\overline{P_{23}(r_2)} & P_{23}(r_2) \\ 0 & 0 & 0 & \overline{P_{23}(r_2)} & P_{23}(r_2) \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

(2)

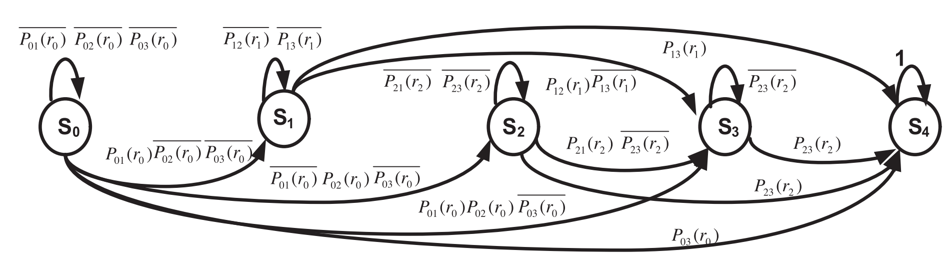


Fig. 4. State transition diagram for the example in Fig. 3.

where each element a_{ij} represents the transition probability from state i to state j, $P_{ij}(r_i)$ is the probability of receiving a packet sent from node i to node j, and $\overline{P_{ij}(r_i)} = 1 - P_{ij}(r_i)$. Note that this probability is a function of the transmission rate r_i. The corresponding state diagram is depicted in Fig. 4. According to Property 1, m_0 represents the expected number of (re)transmissions that are required to deliver a packet from source (node 0) to the destination (node 3), i.e., the expected absorbing time of the Markov chain that starts from state S_0 and absorbed at state S_4), note that m_0 is a function of the transmission rate r_i.

4.2.2. Optimization problem

To facilitate the formulation of our problem, we consider the following property [24]:

Property 2. *Let* **A** *be the transition matrix of a Markov chain, and let* **u** *be a probability vector that represents the initial distribution. Then the probability that the chain is in state S_i after n steps is the ith entry in the vector* $\mathbf{u}^{(n)} = \mathbf{u}\mathbf{A}^n$.

For the example in Fig. 3, we can start with the distribution $\mathbf{u} = [1\,0\,0\,0\,0]$. Note that $\mathbf{u}(0) = 1$ means that the system is in state S_0; the packet is not sent yet. Then, by using Property 2, we find that $\mathbf{u}^{(i)}\mathbf{Nc}$ is the expected number of MASs that will be reserved by the relay nodes in the ith retransmission. Note that $\mathbf{N}$ is a $(2^{nr}+1)$-by-$(nr+1)$ matrix whose entry n_{ij} represents the number of MASs that will be reserved by node j in the state S_i and $\mathbf{c}$ is a column vector whose entries are 1 and its length is $nr+1$. Accordingly, the expected total number of MASs required for the transmission from the source to its destination will be $\sum_{i=1}^{\lceil m_0 \rceil}\mathbf{u}^{(i)}\mathbf{Nc}$. Moreover, by using Property 2, the probability that the system reaches the absorbing state S_4 (i.e., the destination receives the packet) after a given number of retransmissions n is given by $\mathbf{u}(4)^{(n)}$. Therefore, to satisfy a target end-to-end PER ε for a given number of retransmissions n, the condition $(1-\varepsilon) \leqslant \mathbf{u}(4)^{(n)}$ must be satisfied. We limit the possible values of n to the range $1 \leqslant n \leqslant n_{max}$, where the n_{max} is calculated by assuming that all retransmissions are performed by the source itself using the maximum transmission rate for each. Thus, n_{max} satisfies $(\mathrm{PER}_{max})^{n_{max}} \leqslant \varepsilon$, where PER_{max} is the PER for the link between the source and the destination when the maximum transmission rate is used. n_{max} is given by:

$$n_{max} = \left\lceil \frac{\log \varepsilon}{\log \mathrm{PER}_{max}} \right\rceil. \tag{3}$$

where PER_{max} is provided by the physical layer. Accordingly, we can formulate our problem as follows:

$$\min_{\{r:r\in\mathcal{R},n:1\leqslant n\leqslant n_{max}\}} \sum_{i=1}^{n}\mathbf{u}^{(i)}\mathbf{Nc} \quad \text{s.t.} \quad (1-\varepsilon) \leqslant \mathbf{u}(k)^{(n)} \tag{4}$$

where k is the index of the absorbing state.

In Section 6.1, we will illustrate the nonlinear relationship between the transmission rate $r \in \mathcal{R}$, number of MASs, and PER. Therefore, $\mathbf{u}^{(i)}$, $\mathbf{N}$, and m_0 nonlinearly depend on the transmission rates $r \in \mathcal{R}$, which makes our problem hard to solve.

4.3. Complexity

We now show that the problem in Section 4.2 is NP-hard. To do that, we consider a simplified instance of our problem by assuming that there is no relay node between the source and the destination, and the number of retransmissions is limited to a certain value. This simplified instance of our problem is related to the well-known Multiple-Choice Knapsack problem (MCKP).

Definition (*Multiple-Choice Knapsack Problem (MCKP) [25]*). Given y classes $C_1, C_2, \ldots, C_y$ of items to pack a knapsack, where each item $i \in C_j$ has a profit f_{ij} and a weight w_{ij}, the problem is to choose one item from each class such that the profit sum is maximized while the weight sum does not exceed a predefined value.

Now, let the classes of items in MCKP be the sets of transmission rates that can be used in each retransmission process, the knapsack in MCKP be the retransmission processes, and the profit and weight of each item in MCKP be the corresponding number of MASs and the PER of each transmission rate, respectively. Therefore, an instance of MCKP can be converted into an equivalent instance of the rate-assignment problem. Because MCKP is NP-hard [25], our problem is also NP-hard. To address it, we propose in the next section an approximate solution that exhibits reasonable computational/communication overhead.

5. Proposed IMPORTANT scheme

Our approximate IMPORTANT solution can be explained as follows:

- The source S first finds the min-hop path to the destination D by applying Dijkstra's algorithm [26] on the graph determined by the lowest transmission rate; a link exists between two nodes if these nodes can communicate directly at the lowest transmission rate while satisfying a target end-to-end PER. This min-hop path can be considered as a skeleton for the opportunistic route. We call the nodes along this path *skeleton nodes* and their one-hop neighbors as *relay nodes*. According to IMPORTANT, the source, destination, skeleton, and relay nodes need to exchange some information (i.e., the IDs of received packets by each node after each retransmission). The skeleton nodes facilitate the exchange of such information. To illustrate, consider the example in Fig. 5. In this example, we assume the TDMA structure used for WiMedia-based UWB systems. The min-hop path from S to D is $S \rightarrow A \rightarrow B \rightarrow D$. Therefore, the skeleton nodes are A and B (other nodes are relay nodes). S transmits data packets (assume packets 1, 2, and 3 are sent in this example) during its reserved channel time in a superframe. In the next superframe, all the nodes that are participating in the routing process use their beacon frames (during the beacon period) to announce the IDs of their received data packets (see Fig. 5). After that, as we see in Fig. 5, during a pre-reserved channel time, each skeleton node (starting from the closest one toward the destination; node B in this example) announces the packets received by this node and all its one-hop neighbors. Accordingly, as we see in Fig. 5, each node that participates in the routing process will know which packets should be retransmitted by itself during the upcoming retransmission (i.e., a node should resend the packets that were not received by the destination or by other nodes that are closer to the destination than this node). Note that the pre-reserved channel time can be considered as a short beacon period and the skeleton nodes can make their announcements using beacon frames (≈85 μs for each beacon slot). In practice, the number of hops is often lower than 5. Therefore, in one MASs (256 μs), up to four skeleton nodes (i.e., 5-hops path) can make their announcements.
Therefore, the coordination process in IMPORTANT is mainly based on using the beacon frames that already required in UWB network according to the ECMA-368 standard. According to the ECMA-368 specifications, each node in UWB network should send a beacon frame during a predetermined time slot at the beginning of each superframe. So, IMPORTANT does not add a new overhead in terms of the number (same as the number of beacon frames) and the coordination (TDMA structure defined by ECMA-368 standard) of information messages.

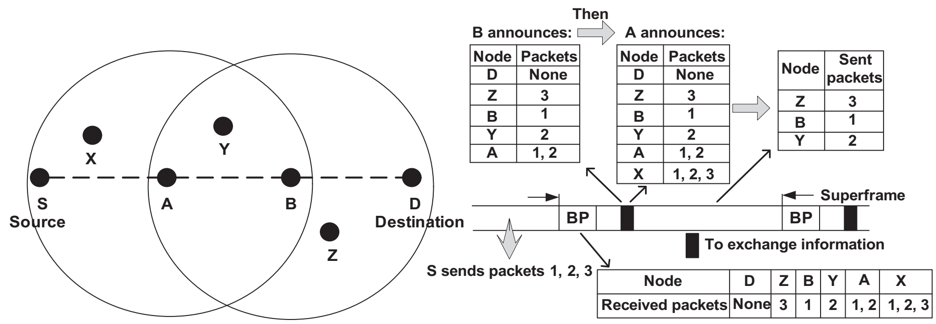


Fig. 5. Example illustrates the proposed IMPORTANT scheme.

Nodes use their beacon frames to send coordination information. These beacons are sent at the lowest transmission rate based on a TDMA structure, and hence there is a low probability of missing these beacons. Moreover, because sending these beacons is done in a fixed time-sequence (i.e., TDMA structure), if one beacon is missed, then the sequence of sending these beacons will be continued (the missed beacon will be announced in the rest of the sequence) but the packet retransmission process is partially done in the current superframe and resumed in the next superframe. To illustrate this process, consider the example in Fig. 5. The sequence of retransmitting packets is as follows: Z (has the highest priority to retransmit packets), B, Y, A, X, S (has the lowest priority to retransmit packets). If the beacon sent by node Y is missed, then nodes Z and B will retransmit their received packets (packets 1 and 3) but nodes A, X, and S will wait for the next superframe to learn what packets will be retransmitted by node Y. Therefore, IMPORTANT will not break down if an information message is missed.

- At the time of reserving the required MASs, the source should determine the number of retransmissions and the transmission rate for each retransmission such that the expected number of reserved MASs is minimized while at the same time a target end-to-end PER is satisfied. According to our proposed solution, this is done as follows. First, the source calculates the maximum possible number of retransmissions, assuming that these retransmissions are all performed by the source itself using the maximum transmission rate for each, i.e., the maximum PER ($\mathrm{PER}_{\max}$) will be considered in each retransmission. In this case, the source would retransmit $n_{\max}$ times to satisfy the target PER (ε), where $n_{\max}$ satisfies $(\mathrm{PER}_{\max})^{n_{\max}} \leqslant \varepsilon$. Thus,

$$n_{\max} = \left\lceil \frac{\log \varepsilon}{\log \mathrm{PER}_{\max}} \right\rceil. \tag{5}$$

After that, for each possible number of retransmissions $n, 1 \leqslant n \leqslant n_{\max}$, the source try to find the best transmission rates (used in the retransmissions) that result in minimum number of MASs and satisfies the target PER. To increase the speed of finding the best transmission rates, the process is started with the best rate assignment with respect to the optimization metric (i.e., minimizing number of MASs), and then gradually change the rate assignment until the feasibility condition (i.e., the target PER) is satisfied. This process is similar to the rate assignment algorithm proposed in [16]. A pseudocode for our proposed rate assignment algorithm is shown in Algorithm 1. The first step in this algorithm is assigning the maximum transmission rate (i.e., r_M) for each retransmission. If this rate assignment satisfies the feasibility condition (i.e., the target PER), then it is the optimal rate assignment because it results in minimum number of MASs and satisfies the target end-to-end PER. Otherwise, the algorithm replaces r_M in one retransmission by the next highest rate (i.e., r_{M-1}). To illustrate, for the first step, if the first rate assignment for $n = 3$ is $\{r_8, r_8, r_8\}$ and the PER related to this transmission rate is PER_8 and with this rate assignment the target end-to-end PER is not satisfied ($(\mathrm{PER}_8)^3 \geqslant \varepsilon$), then the rate assignments $\{r_7, r_8, r_8\}$ is tested. If this rate assignment fails to satisfy the target PER ($\mathrm{PER}_7 \times \mathrm{PER}_8 \times \mathrm{PER}_8 \geqslant \varepsilon$), then the rate assignments $\{r_7, r_7, r_8\}$ is tested. This procedure continues until the feasibility condition is satisfied. In fact, by using this procedure we aim to reduce the PER and reach feasibility with a minimum increment in the number of MASs. Finally, the source node selects the best number of retransmission n (as well as the best rate assignment) that results in minimum number of MASs and satisfies the target PER. It is clear that the order of the selected transmission rates over various hops is not important because the order will not affect our objectives; the end-to-end PER and the total number of MASs reserved over the entire path.

Algorithm 1. Rate Assignment Algorithm

Input: Number of retransmissions $n, \mathcal{R} = \{r_1, r_2, \ldots, r_M\}$
Output: the best (in terms of number of MASs) feasible rate assignment C, or failure if no such rate assignment can be found
Initialization: $C = [r_M, r_M, \ldots, r_M], |C| = n$
for step $= 1$ to $(M-1)n + 1$
  if C is feasible
    return C
    break
  else
    Replace one of the highest transmission rates in C by the next highest rate (i.e., one of r_M is replaced by r_{M-1})
      if C is feasible
        return C
        break
      end
  end
end
return "no feasible rate-assignment found"

Result. Let the optimal number of retransmissions be denoted by n_{opt}, the expected number of MASs returned by the optimal solution be N_{opt}, the expected number of MASs returned by our proposed solution be N_{pro}, and the required number of MASs that should be reserved to satisfy a required traffic load at the minimum and maximum transmission rates be $N_{\min}$ and $N_{\max}$, respectively. Then $N_{\mathrm{opt}} \leqslant N_{\mathrm{pro}} \leqslant \frac{n_{\max}}{n_{\mathrm{opt}}} \frac{N_{\min}}{N_{max}} N_{\mathrm{opt}}$, where $n_{\max}$ was given in (6).

Proof. We know that $n_{\mathrm{opt}} N_{\max} \leqslant N_{\mathrm{opt}}$ and $N_{\mathrm{opt}} \leqslant N_{\mathrm{pro}} \leqslant n_{\max} N_{\min}$. The second inequality can be rewritten as $N_{\mathrm{opt}} \leqslant N_{\mathrm{pro}} \leqslant \frac{n_{\max} N_{\min}}{N_{\mathrm{opt}}} N_{\mathrm{opt}}$. Also, if we replace $\frac{n_{\max} N_{\min}}{N_{\mathrm{opt}}}$ with $\frac{n_{\max} N_{\min}}{n_{\mathrm{opt}} N_{\max}}$, then the inequality is still valid. Therefore, $N_{\mathrm{opt}} \leqslant N_{\mathrm{pro}} \leqslant \frac{n_{\max} N_{\min}}{n_{\mathrm{opt}} N_{\max}} N_{\mathrm{opt}}$. □

Example. Consider the simple UWB network shown in Fig. 6(a). In this network, suppose that the traffic demand from the source S to its destination D is 10 Mbps, the packet size is 200 bytes, and the required end-to-end PER is 0.04. Opportunistic routing is applied to this network. The PER and the number of MASs over a link depend on the transmission rate used over that link (following ECMA-368 specifications, please see Eqs. (8) and (9) in the manuscript). In this example, we consider both an exhaustive search approach and our proposed algorithm "IMPORTANT" to find the best rate assignment (over each link) that minimizes the total number of reserved MASs while satisfying the end-to-end PER. For the exhaustive search, the best transmission rate and the corresponding PER as well as the number of MASs over each link are shown in Fig. 6(b) (the calculations will be explained shortly). Accordingly, the required total number of MASs is $40 + 45 = 85$ and the expected end-to-end PER $= 1 - ((1 - 0.21) + 0.21 \times (1 - 0.11)(1 - 0.09)) = 0.0399$. For IMPORTANT, the results will be as follows (the calculations will be explained shortly). The expected number of a packet transmission is two: the first one is done using the transmission rate of 200 Mbps and the second one is also done using the transmission rate of 200 Mbps. Therefore, the required number of MASs is $45 + 45 = 90$. Note that IMPORTANT algorithm performs all its calculations based on the worst case where the source node will do all the retransmissions. Therefore, the expected end-to-end PER $= 0.18 \times 0.18 = 0.0324$.

This simple example shows that IMPORTANT achieves the end-to-end PER ($0.0324 < 0.04$) and reserves a number of MASs (90) that is very close to the optimal case (85 MASs) found by the exhaustive research.

As for the complexity, in the exhaustive search, we first find the maximum possible number of transmissions of a packet (n_{max}) using the same method used in IMPORTANT (see Equation 7 in the manuscript). For the example shown in Fig. 6(a), we found that the maximum number of possible transmissions of a packet is 3 (calculated in the response of the next comment). If we assume that the allowed number of transmissions is one, then this transmission will be done by the source node S using one transmission rate. Accordingly, we test all the possible transmission rates (8 transmission rates under the ECMA-368 specifications) and select the one that minimizes the number of MASs and satisfies the end-to-end PER. Now if we assume that the allowed number of transmissions is two: the first transmission will be done by the source S and the second transmission is by node A (assuming that A received the first transmission but D did not receive it) or by S (if A did not receive the first transmission). Therefore, we test all the possible combinations of transmission rates over the two transmissions. For two transmissions, the total number of possible combinations is $8*8 + 8*8 = 128$. Similarly, if we assume that the allowed number of transmissions is three, where the first one will be done by node S, the second one will done by A or S, and the third transmission will be done by A or S, then we have to test all the possible 2048 combinations of transmission rates over the three transmissions. Therefore, for this simple example, we have to perform 2184 tests. Finally, we select the number of the transmissions and its corresponding transmission rate assignment that results in the smallest number of MASs and satisfies the required end-to-end PER.

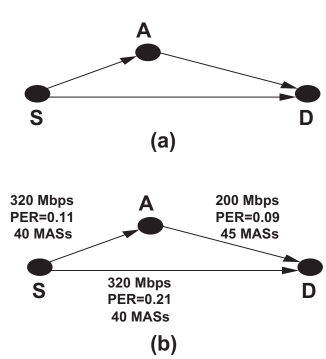


Fig. 6. (a) Example that illustrates an opportunistic routing, and (b) opportunistic routing with an optimal rate assignment that minimizes the total number of reserved MASs while satisfying a target end-to-end PER (obtained through exhaustive search).

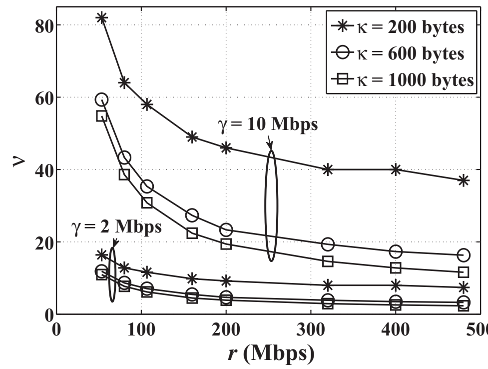


Fig. 7. v vs. r at different γ and κ.

For the IMPORTANT algorithm, we follow the same procedure. We test all possible transmission scenarios and select the one that results in the smallest number of MASs and satisfies the required end-to-end PER. However, the computational complexity is reduced as follows. If we assume that the allowed number of transmissions is one, then this transmission will be done by the source S using one transmission rate. Accordingly, we test all the possible transmission rates (8 transmission rates under the ECMA-368 specifications) and select the one that minimizes the number of MASs and satisfies the end-to-end PER. If we assume that the allowed number of transmissions is two, which are done by node S, we test all the possible combinations of transmission rates over the two transmissions. The algorithm will run $(8 - 1) * 2 + 1$ steps, and in each step it examines two rate assignments (see Algorithm 1). Accordingly, the number of combinations is $((8 - 1) * 2 + 1) * 2 = 30$. If we assume the allowed transmissions are three and all of them are done by the source, then we test all possible combinations of transmission rates over the three transmissions ($((8 - 1) * 3 + 1) * 3 = 66$ combinations). Finally, we select the number of the transmissions and its corresponding transmission rate assignment that results in the smallest number of MASs and satisfies the required end-to-end PER. Therefore, the total number of tests in IMPORTANT algorithm is $8 + 30 + 66 = 104$.

In summary, for the example shown in Fig. 6, 2184 tests are needed to find the optimal transmission rate assignment using the exhaustive search approach. This rate assignment results in reserving 85 MASs and satisfies the target end-to-end PER ($0.0399 < 0.04$). On the other hand, use the IMPORTANT algorithm, we only need to perform 104 tests to find a near-optimal transmission rate that results in 90 MASs and satisfies the target end-to-end PER ($0.0324 < 0.04$).

An upper bound on the expected number of MASs can be obtained from the inequality $N_{opt} \leqslant N_{pro} \leqslant \frac{n_{max} N_{min}}{n_{opt} N_{max}} N_{opt}$. For the example in Fig. 6, $N_{opt} = 85$ MASs, $N_{pro} = 90$ MASs, $N_{min} = 81$ (the number of MASs if the smallest transmission rate is used; this number can be found from Fig. 7), $N_{max} = 39$ (the number of MASs if the largest transmission rate is used; this number can be found from Fig. 7), $n_{opt} = 2$, and n_{max} is calculated using the following equation:

$$n_{\max} = \left\lceil \frac{\log \varepsilon}{\log \mathrm{PER}_{\max}} \right\rceil = \left\lceil \frac{\log 0.04}{\log 0.24} \right\rceil = 3. \quad (6)$$

Therefore, an upper bound on the expected number of MAS is $N_{\mathrm{opt}} \leqslant N_{\mathrm{pro}} \leqslant 3.11 N_{\mathrm{opt}}$.

6. Performance evaluation

6.1. Simulation setup

We study the performance of the IMPORTANT scheme and compare it with the routing techniques in [16–18,5]. In [16,17], the authors proposed two path selection algorithms: flooding-based search algorithm (FBSA) and rate-based search algorithm (RBSA). These algorithms aim at finding a path and a corresponding rate assignment such that the number of reserved MASs along this path is minimized and at the same time a target end-to-end PER is satisfied. In [18], the authors proposed a resource utilization mechanism (RUM) for improving the throughput in multi-rate UWB-based WPANs. The RUM algorithm aims at finding the best transmission strategy that minimizes the number of MASs and satisfies a target end-to-end PER for a packet sent from a source to a destination that can be reached directly at the lowest transmission rate. In other words, RUM assumes the existence of a single-hop path (under the lowest rate) whereas IMPORTANT works for any multi-hop setting. In RUM, three transmission strategies are tested. The first strategy is direct transmission, in which the packet is sent to the destination in one hop using the transmission rate that minimizes the number of MASs and satisfies the target end-to-end PER. The second strategy is opportunistic routing, in which exactly one relay node (i.e., the nearest one to the destination and which received the packet) is used to retransmit the packet if this packet was not already received by the destination in the first transmission (in IMPORTANT, more than one relay are considered). The third strategy is called time spreading technique, in which the same packet is sent twice using two high transmission rates (instead of one transmission at a low transmission rate) such that the total number of reserved MASs is minimized and the end-to-end PER is satisfied. Furthermore, the authors in [18] studied 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 integration, RUM is used to select the best transmission technique and transmission rate over each link of the path provided by AODV. In the next section, we compare IMPORTANT to this AODV-based RUM scheme. To improve the network throughput, the authors in [5] proposed an integrated routing/MAC protocol called ExOR for multi-hop wireless networks. In this protocol, the closest node to the destination that overheard the transmitted packet is chosen to forward that packet. Unlike the work in this paper, the authors in [5] did not integrate rate assignment into opportunistic routing. Therefore, in the next section, we compare the performance of IMPORTANT to the EXOR protocol at different fixed transmission rates. Our results are based on simulation experiments conducted using CSIM (a C-based process-oriented discrete-event simulation package [27]). The determination of interference and noise is done according to the physical (SINR) model. We consider a multi-band UWB WPAN, where 30 nodes are uniformly placed within 20 m × 20 m field. This size is representative of realistic deployment scenarios (e.g., indoor offices, apartments, body-area networks [28]). Nodes are randomly paired. For a given source–destination pair, the session length is randomly selected in the range $[0, 60]$ seconds. Once a session terminates, a new session is immediately initiated with a newly selected duration. For all sessions, the traffic load γ of a reservation is a controllable parameter and is taken to be the same for all sessions. The size of a data packet is set to 1 KB. Other parameter values used in the simulations are given in Table 2. These values correspond to realistic hardware settings [29,10].

Table 2
Parameters used in the simulations.

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

As mentioned before, IMPORTANT exploits the dependence among the multi-rate capability of an OFDM-based UWB system, the number of required MASs for a reservation, and the PER. Therefore, it is worth clarifying such dependence. A given traffic demand γ (in bps) must first be packetized before being transported. Let κ be the payload portion of a packet (in bytes), v the number of MASs that should be reserved in a superframe, and ξ the number of packets corresponding to the demand γ that should be sent per superframe. Then,

$$\xi = \left\lceil \frac{\gamma \lambda_{sp}}{8\kappa} \right\rceil \quad (7)$$

where $\lambda_{sp} = 65.536$ msec is the superframe interval. Let λ_f be the amount of time needed to transmit these ξ packets. Then,

$$v = \left\lceil \frac{\lambda_f}{\lambda_{ms}} \right\rceil \quad \text{slots} \quad (8)$$

where $\lambda_{ms} = 256$ μs is the MAS duration. Next, we explain how λ_f is impacted by the transmission rate r. Note that $\lambda_f = \xi(\lambda_p + \mathrm{SIPS})$ seconds, where SIPS $= 10$ μs is the short inter-packet spacing [10] and λ_p is a packet transmission time. This λ_p is given by $\lambda_p = \lambda_m + \lambda_h + \lambda_u$ seconds, where $\lambda_m = 5.625$ μs is the preamble interval (used for synchronization, carrier-offset recovery, and channel estimation), $\lambda_h = 3.75$ μs is the header interval, and λ_u is the transmission time of a PHY service data unit. Note that λ_m and λ_h are fixed, and only λ_u varies with r. As given in the ECMA-368 standard, λ_u can be expressed as:

$$\lambda_u = 6 \times \left\lceil \frac{8\kappa + 38}{\varrho} \right\rceil \times \lambda_{sy} \quad \text{sec} \quad (9)$$

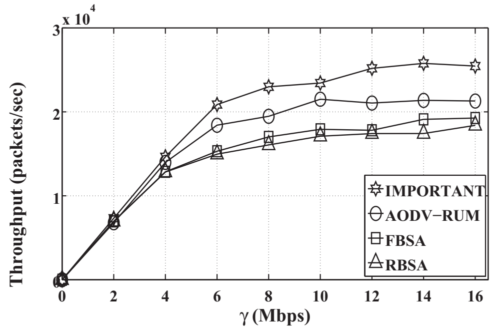
where $\lambda_{sy} = 0.3125$ μs is the symbol interval and ϱ is the number of information bits per 6 OFDM symbols, which depends on r, as shown in Table 3.

The above straightforward analysis allows us to express v as a function of r for various values of γ and κ, as shown in Fig. 7. It can be seen that as γ increases, v becomes more sensitive to r. Furthermore, for given γ and r (e.g., $\gamma = 10$ Mbps and $r = 480$ Mbps), v expectedly decreases with κ, but in a sub-linear fashion. This can be explained by noting the nonlinear relationship between λ_f and κ.

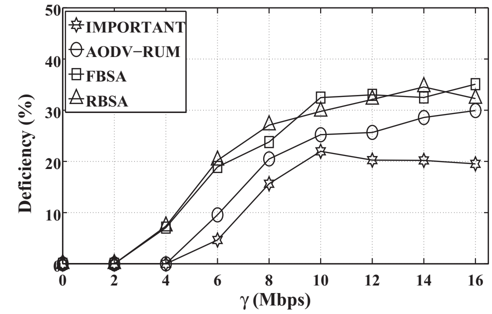
Next, we explore the relationship between r and the PER. Devices can estimate the probability of correct packet/bit delivery

Table 3
Rate-dependent modulation and coding parameters in ECMA-368.

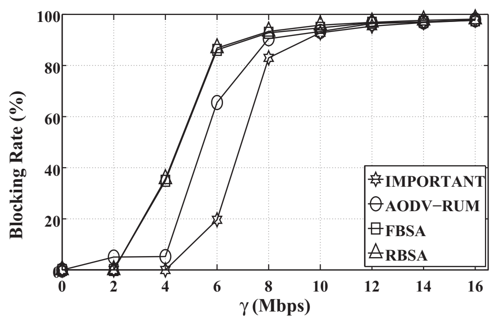
r Mbps	Modulation type	Coding rate	ϱ
53.3	QPSK	1/3	100
80	QPSK	1/2	150
106.7	QPSK	1/3	200
160	QPSK	1/2	300
200	QPSK	5/8	375
320	DCM	1/2	600
400	DCM	5/8	750
480	DCM	3/4	900



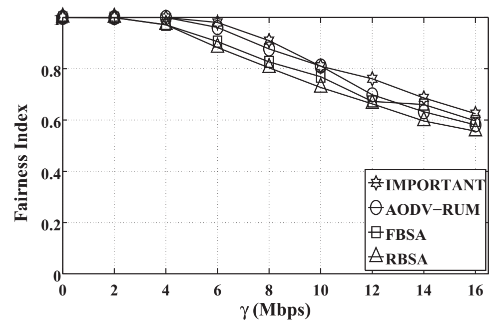
(a) Network throughput.



(b) Deficiency.

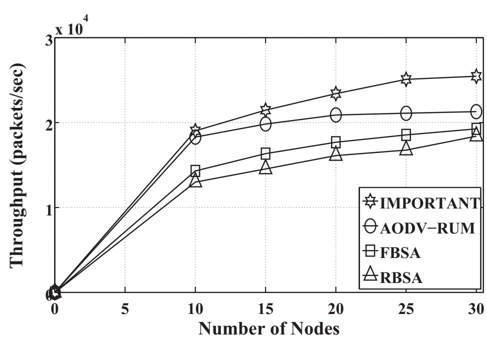


(c) Blocking rate.

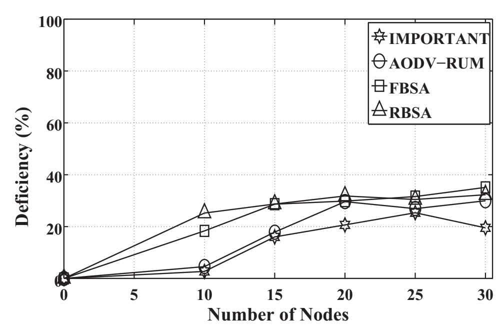


(d) Throughput fairness.

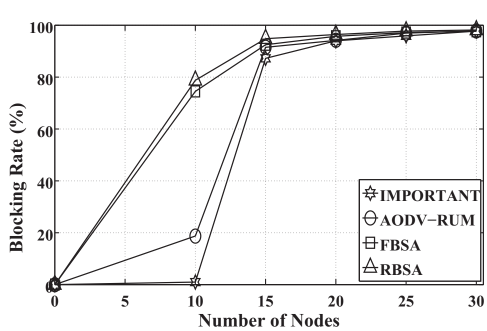
Fig. 8. Performance of various routing protocols vs. traffic load γ.



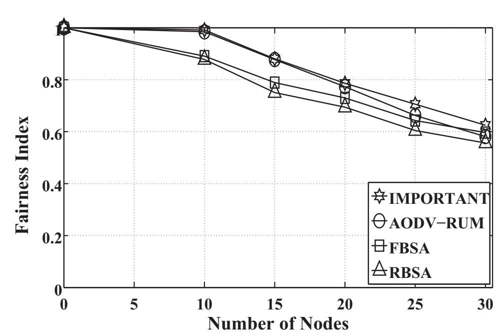
(a) Network throughput.



(b) Deficiency.

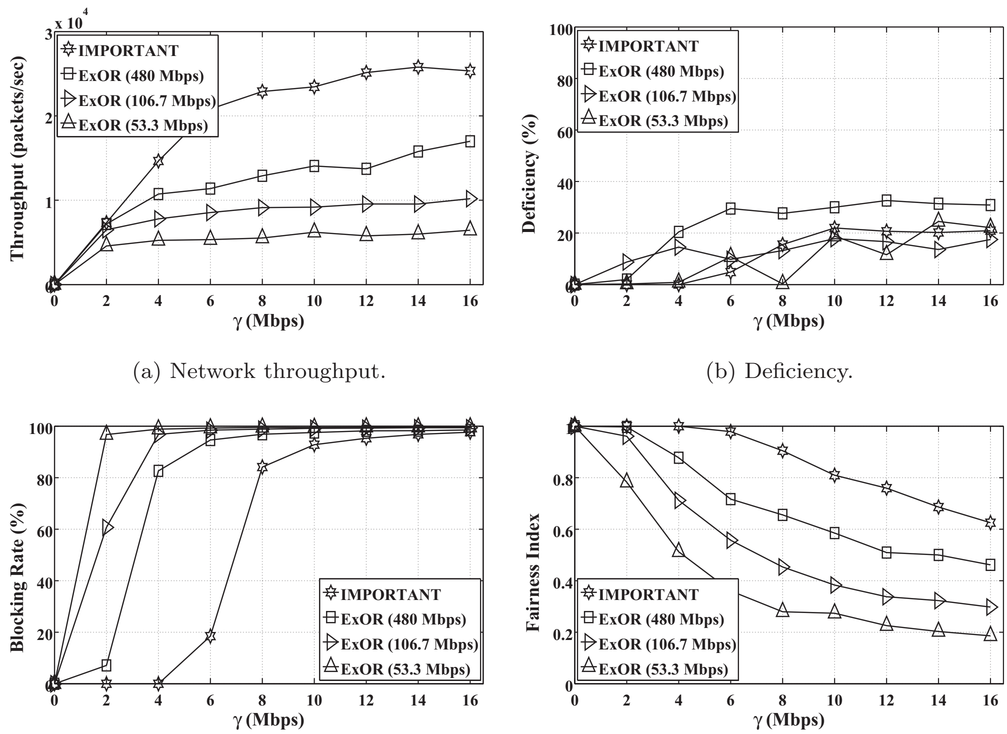


(c) Blocking rate.



(d) Throughput fairness.

Fig. 9. Performance of various routing protocols vs. number of nodes ($\gamma = 16$ Mbps).



(a) Network throughput.

(b) Deficiency.

(c) Blocking rate.

(d) Throughput fairness.

Fig. 10. Performance of various routing protocols vs. traffic load γ.

based on the received SNR or using historical data of the number of packets or bits sent and received over a link. This information can then be used to obtain the PER-vs.-SNR curves [30]. In [31], to reduce the computation time, the authors derived a reasonably accurate yet simple approximation of such curves. In our work, we assume that the PER-vs.-SNR curves are provided by the physical layer. For our simulation purposes, to generate these curves, we extract the BER from the BER-vs.-SNR curves given in [32] (one curve for each transmission rate), and calculate the PER as:

$$PER = 1 - (1 - BER)^{8\kappa}. \quad (10)$$

Note that (10) assumes independence between bits in a packet.

6.2. Results

We focus on four performance metrics: (1) network throughput (i.e., goodput), (2) Jain's fairness index (i.e., throughput fairness) [33], (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 demand 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. 8 depicts the various performance metrics vs. γ. In this figure, we compare the performance of IMPORTANT with FBSA, RBSA, and AODV-with-RUM. As shown in Fig. 8(a), IMPORTANT achieves a significant throughput improvement relative to AODV-with-RUM (21%), FBSA (42%), and RBSA (48%). Figs. 8(b) and (c) shows that, compared with other routing protocols, IMPORTANT achieves lower blocking rate and deficiency. It also provides higher fairness index (more requests are admitted) than the other compared schemes, as shown in Fig. 8(d). From Fig. 8, it can be seen that throughput increases continuously as γ increases even though blocking rate is close to 100%. This can be explained as follows. To establish a session between two nodes, a source node starts by checking the available channel time, i.e., unreserved MASs in the superframe. For the assumed elastic traffic, the session can be established using whatever channel time is available (but without exceeding 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 blocking rate as the ratio between the number of blocked sessions and the total number of generated sessions. So, a high value of γ (i.e., a high traffic demand) means that a high number of MASs is required for one session. Hence, the entire superframe will be reserved (so, high throughput) by a few sessions; the remaining sessions will be blocked, resulting in a high blocking rate.

Fig. 9 depicts the performance as a function of the total number of nodes in the network. As shown in this figure, IMPORTANT achieves high network performance relative to the compared protocols. The results in Fig. 9 support the trends in Fig. 8.

In Fig. 10, we compare the performance of IMPORTANT with that of ExOR [5]. Since there is no rate assignment mechanism in ExOR, we study its performance at different transmission rates (i.e., 53.3, 106.7, and 480 Mbps). In this experiment, we aim at showing that integrating rate assignment into opportunistic routing achieves high performance gain. Fig. 10 shows that IMPORTANT achieves high performance gain relative to ExOR. The performance behavior of ExOR can be explained as follows. It is known that using a high transmission rate results in high PER. Hence, at a high transmission rate (e.g., 480 Mbps), ExOR needs a higher number of retransmissions to satisfy the target end-to-end PER. Therefore, more MASs should be reserved, even though the number of MASs per retransmission is small. It is clear from Fig. 10 that using high transmission rate finely increases the number of MASs relative to using a low transmission rate. Accordingly, a high transmission rate achieves higher performance than a low transmission rate.

7. Conclusions

In this paper, we studied and formulated the integration of rate assignment into opportunistic routing in UWB-based ad hoc network. In this integration, we aim at minimizing the total number of MASs that should be reserved during relaying a packet to its destination while at the same time a target end-to-end PER is satisfied. We showed that this integration is NP-hard problem, hence we proposed an approximate solution called IMPORTANT protocol. In this protocol, the source node determines the required number of retransmissions for opportunistic routing and the rate assignment per retransmission such that our mentioned aims are satisfied. Extensive simulations showed that IMPORTANT significantly improves network throughput (up to 21–48%) compared to several routing techniques (FBSA, RBSA, AODV-RUM, and ExOR).

Acknowledgement

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