Economy: A Duplicate Free Opportunistic Routing

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ABSTRACT
This paper proposes ECONOMY, an Opportunistic Routing (OR) protocol that is free from duplicate transmission. OR utilizes overheard packets and takes multiple routes into consideration concurrently. It has been shown that OR outperforms traditional routing by close to 100% in term of throughput; however, duplicate transmissions may occur as relays cannot hear one another, and it consequently degrades the performance of OR. ECONOMY uses token passing along a path that relays can hear one another to eliminate duplicate transmission. When a token arrives, the relay is allowed to transmit unacknowledged packets according to the acknowledgement information within the received token. Therefore, ECONOMY can prevent duplicate transmission while keeping the advantages of OR. Simulation results show that while previous OR schemes suffer from duplicate transmission, ECONOMY can exploit the potential of OR and perform up to 100% better than traditional routing.

Categories and Subject Descriptors

General Terms
Algorithms, Design, Performance

Keywords
Wireless networks, Opportunistic Routing

1. INTRODUCTION
In recent years, wireless communication has become an important part of our daily life. Despite extensive research efforts and the development of numerous wireless network applications, the potential of wireless medium has not been fully exploited. A special attribute of wireless medium is that each transmission is a broadcast to all neighbors within transmission range; and such a broadcast leads to signal interference. However, opportunistic routing (denoted as OR) can utilize this broadcast attribute to improve link reliability and system throughput by routing packets through multiple routes dynamically. OR can be applied to all kinds of wireless networks, such as ad hoc, mesh, or sensor networks, as long as omni-directional antennas are used. Moreover, both theoretical [1,2] analysis and experimental [4,8] results have shown that OR outperforms traditional routing by around 100% in term of throughput.

Though OR is powerful, one outstanding issue remains - duplicate transmission. Duplicate transmissions degrades performance of OR when relays cannot hear one another; and the issue or the scenario has not been discussed nor solved in previous works (such as ExOR [3,4], GOR [5,6,7], MORE [8]). This paper shows the impact of duplicate transmissions and proposes a solution that can overcome this issue so as to exploit the potential of OR.

1.1 Basic concepts of OR
Opportunistic Routing is a concept that utilizes the overhearing of packets so that they are forwarded through multiple routes where possible. Consider the example as shown in Fig. 1. Two routes are available from S to D; however, OR does not pick either S→X→D or S→Y→D. The decision is made dynamically based on which packet(s) the relays (X and Y in the example) have received. In the example, OR may work as follows: S broadcasts five packets; X receives packets \{1,2,3\}; Y receives packets \{1,2,4,5\}. After coordination, X sends packet \{1,2,3\} and then Y sends what X did not send, i.e. packets \{4,5\}. As a result, packets \{1,2,3\} are routed through S→X→D; and packets \{4,5\} are routed through S→Y→D.

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Figure 1. An illustrated example of OR.

To see the advantage of the concept, let us compare it with traditional routing. Traditional routing picks a predefined route, either S→X→D or S→Y→D. If route S→X→D is selected, packets from S to X are also heard by Y. However, Y may happen to successfully receive some packets, which X failed to do. It is a
pity to drop those overheard packets and then retransmit from S. The same situation happens if another route $S \rightarrow Y \rightarrow D$ is selected.

Unlike traditional routing schemes, OR utilizes overheard packets and uses two routes at the same time. Therefore, OR can send packets with fewer transmission attempts; in other words, higher performance.

### 1.2 Strength and weakness of OR

The strength of OR is obvious: since packet overhearing and multiple routes are taken into consideration simultaneously, OR can improve reliability, and reach further per transmission.

Consider the example as shown in Fig. 2. Assume that Packet Receive Rate (PRR) of link $S \rightarrow R_1$ and $R_1 \rightarrow D$ is 95%; PRR of link $S \rightarrow D$ is 53%. Traditional routing algorithm will select $S \rightarrow R_1 \rightarrow D$; as a result, average transmission attempts required for passing a packet from $S$ to $D$ is always more than 2. However, if OR is applied, packets may be routed through either $S \rightarrow R_1 \rightarrow D$ or $S \rightarrow D$. From the simulation results shown in table 1, the Attempts/Arrived (AA) ratio of OR is fewer than 2. Therefore, OR has the potential to outperform traditional routing.

![Figure 2. An illustrated example of the strength of OR.](image)

### Table 1. Simulation results for the example of Fig. 2

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Throughput</th>
<th>AA ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>ExOR</td>
<td>315.8kbps</td>
<td>1.46</td>
</tr>
<tr>
<td>ECONOMY</td>
<td>242.2kbps</td>
<td>1.43</td>
</tr>
</tbody>
</table>

Though the concept of OR is powerful, the coordination among relays to prevent collisions and duplicate transmissions is an issue. Current OR schemes (such as ExOR [3,4]) coordinate through timers and overhearing. After a sender broadcast packets, relays set timers based on a predefined priority (usually by ETX [9] or geographical distance). If a relay overhears any packet, the timer is paused and the relay also learns what other relays have sent. Let us consider the example in Fig. 1 again; assume that the predefined order is $X$ then $Y$. First, $S$ broadcasts packets. $X$ then starts sending what it has received. At the same time, $Y$ overhears packets from $X$, pauses its timer and learned that $X$ sent packets $\{1,2,3\}$. Finally, $Y$ sends packets $\{4,5\}$.

For the coordination based on overhearing, an intuitive question is what if relays cannot hear one another? In the example of Fig. 1, $Y$ may send packets $\{1,2,4,5\}$ rather than $\{4,5\}$ because $Y$ does not know $\{1,2\}$ have been transmitted by $X$. Besides, both of $X$ and $Y$ may send packets simultaneously and produces collisions at $D$.

![Figure 3. An illustrated example of the weakness of OR.](image)

To further verify the assumption, consider the example in Fig. 3. Assume that PRR of link $R_1 \rightarrow R_2$ and $S \rightarrow D$ is only 17%; therefore, coordination by overhearing is difficult. In the example, the key point is the AA ratio with/without $R_2$ in table 2. As shown, AA ratio increases from 3.1 to 3.5 simply by adding $R_2$. In other words, duplicate transmission does occur in the case when relays cannot hear one another. Simulation results in section 4 also reveal that when the attempts of all relays exceed network capacity, the performance drops.

### Table 2. Simulation results for the example of Fig. 3

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Throughput</th>
<th>AA ratio</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>ExOR</td>
<td>216.8kbps</td>
<td>3.12</td>
<td>Without R2</td>
</tr>
<tr>
<td>ExOR</td>
<td>206.7kbps</td>
<td>3.54</td>
<td>With R2</td>
</tr>
<tr>
<td>ECONOMY</td>
<td>143.8kbps</td>
<td>2.56</td>
<td>Without R2</td>
</tr>
<tr>
<td>ECONOMY</td>
<td>143.8kbps</td>
<td>2.56</td>
<td>With R2</td>
</tr>
</tbody>
</table>

This paper studies the issue of duplicate transmission in OR and develops an OR protocol that has the following features and contributions:

1. Free from duplicate transmission.
2. No longer limited by batches as other OR protocols (e.g. ExOR, MORE).
3. Guarantee 100% transmission (due to overhead, ExOR only guarantees 90%; the rest of 10% is transmitted by traditional routing).

The rest of the paper is organized as follows. Section 2 briefly surveys related works. Section 3 presents the design of ECONOMY. Section 4 shows simulation results and comparison with other OR schemes. Conclusion and future works are presented at section 5.
2. RELATED WORKS

2.1 ETX

ETX [9] refers to “expected transmission count”, i.e. number of transmission required to pass a packet from source to destination. For example, for a link with PRR = 50%, ETX of the link = 1/0.5 + 1/0.5 = 4; 2 for packet transmission and another 2 for acknowledgement. In other words, 4 transmissions on average are required to pass a packet through the link. ETX is a common metric for route selection.

2.2 ExOR (Extremely Opportunistic Routing)

ExOR [3,4] is the first implementation of OR and shows the potential of OR. ExOR schedules relay order and prevents duplicate transmission by overhearing; therefore, collision may occur. Regarding to relay selection, ExOR optimizes by simulating and excludes relays which forward traffic less than 10%. Due to coordination overhead, ExOR uses batch transmission; collecting a predefined number of packets into a batch. When 90% of packets in the batch have been acknowledged, ExOR advances to the next batch.

ExOR works as follows: First, relays are ordered by ETX to destination and transmission starts from high priority (lower ETX) to low priority relays. A relay finds out when its turn comes by overhearing others. In the case when relays cannot hear anything (such as destination), the relay schedules by assuming each of other relay sends 5 packets. Take Fig. 3 for example; assume that ETX priority is S < R2 < R1 < D. When R1 hears transmission from D (D sends acknowledgement), R1 schedules to start transmission after D is done. On the other hand, R2 cannot hear R1 but can hear D. Therefore, R2 assumes R1 sends 5 packets and schedules to start transmission when R1 is sending 6th packet.

The main drawbacks of scheduling by overhearing are: 1) deaf scheduling, relays (such as D in example of Fig.3) has to guess when its turn comes; as a result, collision may occur. 2) scheduling interference, due to collision, a relay may hear packets from multiple sources; therefore, the relay is confused to schedule. Because of these unpredictable behaviors of scheduling by overhearing, AA ratio of ExOR is higher than ECONOMY as shown in table 2.

2.3 GOR (Geographical Opportunistic Routing)

GOR [5,6,7] is the OR based on geographical routing [10], where relay selection is according to geographical position. Its coordination is similar to ExOR: timer and overhearing; and the issue of duplicate transmission is not discussed as well. The main contribution is to show that giving high priority to the furthest link is not always the best choice and proposed another metric EOT (Expected One-hop Throughput) to order relays.

2.4 MORE (MAC-independent OR & Encoding)

Unlike other OR schemes, MORE [8] is the first one to adopt network coding [11] as the coordination method. Such solution bypasses the coordination issue and prevents duplicate transmission. The key concept is that a relay generates a random linear combination of collected packets rather than forwarding them directly; therefore, each transmission (coded packet) is unique. After the destination has collected enough linear independent coded packets, original (non-coded) packets can be restored by Gaussian elimination [12].

Though MORE can prevent duplicate transmission by network coding, it still has the issue of redundant packets. If a destination only needs m linear independent coded packets but it receives n, where n\(>\)m, (n-m) of them are redundant.

3. THE DESIGN OF ECONOMY

In order to deal with OR coordination between relays that cannot hear one another, ECONOMY excludes these “bad” relays by finding a connected candidate order. For scheduling, ECONOMY uses token passing. Only the token holder is allowed to transmit packets. With the combination of connected candidate order and token passing, ECONOMY can prevent duplicate transmission while keeping advantages of OR.

In ECONOMY, each node maintains a packet buffer and an ACK manager. ACK manager records a list of acknowledged SN and is updated whenever a token arrives. Packet buffer keeps all unacknowledged overheard packets. If a packet is acknowledged, it will be removed from packet buffer.

The current design of ECONOMY considers only single flow, and assumes that ETX of each relay to source/destination are known in advance. Extending the work to multiple-flow scenario is part of our future works.

3.1 Packet format

There are two kinds of packets in ECONOMY: data packet and token.

(a) Data packet.

(b) Token.

3.2 THE DESIGN OF ECONOMY

Data packet is created by adding ECONOMY header to the original packet from upper layer. The header includes a sequence number (SN) and ETX of the route from the sender to destination.

Token is a control packet which includes source address and acknowledgements. There are two types of acknowledgement: 1) cumulateACK, all SN up to this number have already been acknowledged, and 2) discreteACK, a list of SN which are acknowledged but not in the range of cumulateACK. Acknowledges in a token are updated before each forwarding.
Consider the example in Fig. 5. Packets from S to D with SN from 0-99 have been acknowledged, and SN\{101,102,104\} also have been acknowledged. Then, cumulativeACK=99; discreteACK is a list of \{101,102,104\}.

3.2 Connected candidate order
Due to coordination difficulty when relays cannot hear one another, ECONOMY uses connected candidate order. The Connected candidate order is a list of relays where \(i\)th relay can hear \((i+1)\)th relay (i.e. PRR of the link is above a threshold). Consider an example in Fig. 7, \{S,R4,R3,R2,R1,D\} is a connected candidate order; \{S,R4,R3,R2,D\} and \{S,R4,R3,R1,D\} are also connected candidate orders. On the other hand, \{S,R5,R4,R3,R2,D\} is not because R5 cannot hear R4.

3.3 Token passing
Each token contains two messages: 1) the transmission right, relays are allowed to transmit packets only when they get a token. 2) a list of acknowledged SNs, so that relays can know what others have received and prevent duplicate transmission.

Token is generated from destination and passed backward to source along the connected candidate order by using unicast with RTS/CTS mode. Once a token reaches source, the token is dropped. Multiple tokens are allowed and the token generation speed is controlled by destination. To prevent the case when a token is caught up by the next token, a token holder sends token only when it does not overhear anything.

Consider the topology in Fig. 7 and connected candidate order \{S,R4,R3,R2,R1,D\}. First, a token is generated by D and send to R1 by unicast. With information in the token, R1 sends data packets which have not been acknowledged by D; and then forwards the token to R2. Because TG-timer is reset whenever D hears any packet, the TG-timer in D is reset again and again during the transmission of R1; as a result, no token is generated from D. After R2 completes transmission and pass the token to R3, the new token holder R3 can no longer be heard by D. Finally, D generates a new token and sends it to R1.

3.4 Picking the next token holder
Tokens are forwarded through the connected candidate order; and each relay picks the next token holder locally. A relay picks the next token holder among neighbors, which are closer to source (comparing to the relay), and selects the furthest one. In other words, all neighbors whose ETXs (to source) are smaller than that of the relay are considered to be candidates, and pick the one with the highest ETX (to source).

Figure 7. An illustrated example of token passing of ECONOMY.

Consider the topology in Fig. 7 and connected candidate order \{S,R4,R3,R2,R1,D\}. Among them, R4 and R3 are closer to source than R2 because the ETX of R3 and R4 to source are lower than that of R2. Among R3 (ETXR3→S=5) and R4 (ETXR4→S=2.5), R2 picks R3 as the next token holder because R3 has higher ETX (to source) than R4.

Current simulation results shows that the connected candidate order selected by the policy above can prevent duplicate transmission; however, what is the best connected candidate order is still unknown. It is part of our future works.
3.5 Data packet collection & transmission

Relays collect overheard packets. A packet is put into packet buffer only when 1) the packet is not acknowledged, and 2) ETX of the sender to destination is higher than that of the relay.

The transmission of data packets is triggered only when a token is received. Once a token arrives, the relay updates ACK manager according to SN list in the token, and removes acknowledged data packets from packet buffer. Then, the relay sends all data packets in packet buffer. Finally, the relay forwards the token to the next one along the connected candidate order.

Regarding to retransmission, a relay cannot tell if a transmission is successful or not with broadcasting. Once a transmission failed (a packet is not received by any other relay), the relay is notified to forward the packet at the next time a token arrives.

Consider the topology in Fig. 7. R2 only collects data packets from R3 and R4 and ignores data packets from R1 because R1 is closer to destination. Once a token arrives, R2 updates ACK manager and removes data packets which have been acknowledged by D and R1. Then, R2 broadcast all the remaining data packets in its packet buffer. If a packet from R2 is received by neither R1 nor D; the packet will be retransmitted at the next time R2 receives a token.

4. PERFORMANCE EVALUATION

This section presents simulation results of 3 routing schemes: ECONOMY, ExOR, and traditional routing based on ETX (denoted as TR-ETX). All these schemes use the same ETX information. The simulation is implemented in QUALNET system.

4.1 Simulation parameters

In the simulated system, the batch size of ExOR is set to 100. Traditional routing selects routes according to ETX.

At the beginning of each instance, nodes send probes to neighbors so as to get ETX of nearby links. Then, do route discovery and get ETX of routes by flooding. All these 3 schemes use the same ETX information. At last, traffic comes in and the program starts collecting statistics. The simulation results are averages of 100 instances. Table 3 summarizes all parameter assumptions.

<table>
<thead>
<tr>
<th>Simulation Parameters</th>
<th>Traffic parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHY</td>
<td>Traffic type</td>
</tr>
<tr>
<td>Power</td>
<td>CBR</td>
</tr>
<tr>
<td>Data rate</td>
<td>1024 Bytes</td>
</tr>
<tr>
<td>Fading model</td>
<td>Interval between packets</td>
</tr>
<tr>
<td>Number of instances</td>
<td>0.02 Sec</td>
</tr>
<tr>
<td>ETX parameters</td>
<td>Duration</td>
</tr>
<tr>
<td>Probe size</td>
<td>500 Sec</td>
</tr>
<tr>
<td>Number of probes</td>
<td></td>
</tr>
<tr>
<td>Interval between probes</td>
<td></td>
</tr>
</tbody>
</table>

Uniform distribution is considered in the simulation. The simulated environment is divided into n*n square grids with one node in each grid. Position of the node in a grid is randomly distributed. Grid size is 200(m)*200(m); PRR of a 400m-link is about 65%. For route length=1, there are (2^1)*2=4 nodes; for route length=2, there are (2^2)*4=16 nodes; for route length=3, there are (2^3)*6=36 nodes; for route length=4, there are (2^4)*8=64 nodes. A source is always at upper left corner and a destination is at lower right; position of destination varies as route length changes.

4.2 AA ratio (Attempts/Arrivals)

To understand the influence of duplicate transmission, AA metric is considered in the simulation. AA ratio refers to number of transmission attempts required at MAC layer for a single message arrived at application layer of destination. Transmission only refers to data packets and control messages are not included. Transmission attempts include attempts of source and all other relays. In short, AA ratio is a metric to evaluate duplicate transmission. For the example of Fig. 2; assume S sends 125 packets, R1 forwards 50 packets; D receives 100 packets. Then, AA ratio = (125+50)/100 = 1.75.

Calculating AA ratio of traditional routing is a little bit different from that of OR schemes. Because traditional routing uses unicast, a successful transmission is recorded as one attempt no matter how many retransmissions are triggered. In other words, AA ratio of traditional routing means hop counts of the best route selected by traditional routing.

4.3 Results and discussions

Two simulation results are presented: throughput and AA ratio.
Throughput of traditional routing is better than that of OR when route length is small (route length=1). It is because destination can directly receive packets from source; therefore, OR is useless. Though AA ratios of all schemes are similar, throughputs of OR are lower due to coordination overhead.

On the other hand, as route length grows, ECONOMY shows the strength of OR with fewer transmission attempts. AA ratio of ECONOMY is even lower than that of traditional routing. As a result, ECONOMY performs about 100% better than that of traditional routing.

What interesting is the result of ExOR. When route length=2, its performance is between ECONOMY and traditional routing; but its performance drops and becomes worse than traditional routing as route length increases to 4. To explain this trend, please also take a look at the simple simulations in section 1.2 and 1.3. Though ExOR has OR properties (example of Fig. 2), it induces duplicate transmissions when relays cannot hear one another (example of Fig.3). These duplicate packets result more duplicate packets. When overall transmission exceeds network capacity, the system throughput collapses. As route length=4, AA ratio of ExOR is about 100% higher than ECONOMY and thus the throughput of ECONOMY is 100% better than that of ExOR.

In the future, find the best connected candidate order will be studied and extend ECONOMY to multi-flow and mobility scenario.

6. ACKNOWLEDGMENTS
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7. REFERENCES