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Corridor-based Routing: Constructing and Maintaining Stable Support-Structures for Wireless Multihop Transmissions

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***Abstract*—Conventional shortest path routing protocols suffer from short link lifetime and require much effort for route recovery. Corridor-based routing aims at providing a stable support structure for wireless multihop networks, thus enabling high data throughput. The intermediate hops within the corridor contain multiple nodes, which cooperate and forward data jointly to exploit the diversity of links within the corridor. In this work, we propose a cross-layer approach for corridor construction taking the estimated link lifetime into account. Furthermore, a concept for corridor maintenance is introduced which can adapt the corridor to changes of the network caused by node movements. In combination with a novel resource allocation scheme based on OFDMA, corridor-based routing achieves significant throughput gains and higher stability compared to shortest path routing.**

I. Introduction

Conventional routing schemes, such as Dynamic Source Routing (DSR) [1] and Ad hoc On Distance Vector (AODV) Routing [2], are strictly limited to the network layer and use the number of hops as a metric to find an end-to-end path between a source and a destination. The resulting path often consists of weak links between distant forwarding nodes [3]. Due to movements of the nodes, these links can break quickly. This short link lifetime limits the achievable throughput and causes much effort for route recovery. To reduce the route recovery overhead and to increase the stability of routes, some protocols take physical layer information in terms of the link strength [4] or the link stability [5] into account. In [3], signal strength is monitored to estimate the link lifetime and to increase the stability of routes.

State-of-the-art physical layers such as Orthogonal Frequency Division Multiple Access (OFDMA) are well studied for one-hop communications and enable significantly higher data throughput by exploiting spatial diversity. To achieve a diversity gain also for multihop transmissions, in [6] and [7], a network with multiple possible relay nodes at each hop is considered. In [6], different relay selection schemes are proposed for a single carrier transmission based on cooperation of the nodes. In [7], a multi carrier transmission is considered with an individual relay selection for each subcarrier.

In corridor-based routing [8], we follow a similar approach. A multihop structure consisting of multiple possible forwarding nodes forms the corridor which is used to enable the exploitation of link diversity based on OFDMA. Unlike [7], corridor-based routing considers the possibility of splitting and joining data within the corridor, i.e., each forwarding node can split the received data and forward it to different receiving nodes according to the current channel conditions [8]. To avoid collisions, an exclusive subcarrier allocation in each hop is used requiring the local cooperation of the forwarding nodes. Thereby, the corridor allows a fast adaptation to the dynamic wireless channel based on local resource allocation. Furthermore, long-term variations of the link quality can be taken into account on a slower time scale by adapting the corridor itself, i.e., by selecting the nodes which are part of the corridor. The corridor construction has been considered in [9] and [10]. In [9], the corridor is built based on geographic routing and geometric criteria. In [10] the overhead introduced by the corridor construction is investigated and the turning point at which corridors pay off is determined by means of simulations and practical implementation on software-defined radios. In both works, information concerning the positions of the nodes is required to build the corridor. Furthermore, only static scenarios are considered.

The presented schemes in this paper do not rely on position knowledge. Furthermore, we consider dynamic networks and evaluate the stability of the corridor. In this work, the following contributions are provided:

1) We extend a corridor construction procedure by taking the estimated link lifetime into account.
2) We introduce a concept to maintain the corridor structure in dynamic networks.
3) We design a novel resource allocation strategy which takes 2-hop average link quality into account.
4) We evaluate the performance of corridor-based routing in dynamic networks.

The rest of the paper is organized as follows. The system model is introduced in Section II. In Section III, we introduce the corridor construction, corridor maintenance and the resource allocation scheme. Section IV evaluates the performance of the proposed schemes and Section V concludes the paper.

II. System model

We consider a multi-hop transmission between one source node S and one destination node D over N_{H} hops. The intermediate hops between S and D consist of multiple possible forwarding nodes as shown in Fig. 1. In hop h, the number of transmitters is given by $N_{\mathrm{T}}^{(h)}$ and the number of receivers is given by $N_{\mathrm{R}}^{(h)}$, leading to $N_{\mathrm{T}}^{(1)} = 1$ (S) and $N_{\mathrm{R}}^{(N_{\mathrm{H}})} = 1$ (D). The transmission is based on OFDMA and the available bandwidth B is subdivided into N orthogonal subcarriers. For the transmission in each hop, an exclusive subcarrier allocation is applied, i.e., there is only one node transmitting on a subcarrier at a time to only one receiving node. On each subcarrier, different data is transmitted. Furthermore, only the transmitters of one hop are transmitting at a time. Therefore, no collisions occur. The forwarding nodes employ the decode-and-forward protocol, i.e., received messages are decoded and re-encoded at the nodes. Therefore, no noise is forwarded by the nodes. On the channels between the nodes,

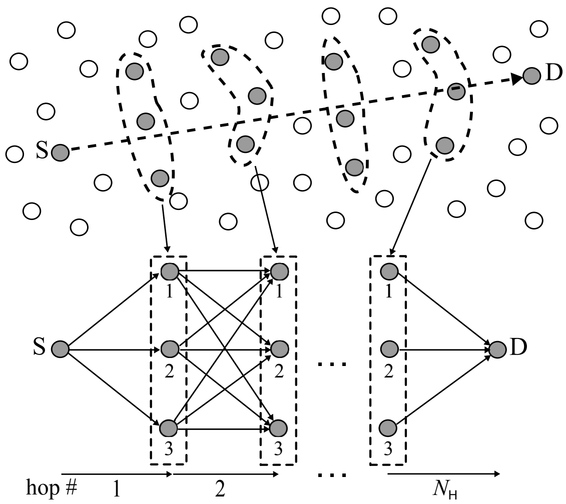

Fig. 1: Multi-hop corridor system model with $N_{\mathrm{T}}^{(h)} = 3$ for $h = 2, ..., N_{\mathrm{H}}$

Rayleigh fading is assumed. The channel between node i and node j in hop h concerning subcarrier n is described by the transfer factor $H_{i,j,n}^{(h)}$ which is modeled as a complex Gaussian distributed random process with variance one. The average noise power per subcarrier is denoted by σ^2. The transmit power of node i in hop h on subcarrier n is given by $p_{i,n}^{(h)}$. The average transmit power per subcarrier is normalized to one. Hence, the overall transmit power per hop is given by $P_{\mathrm{T}} = \sum_{n=1}^{N} \sum_{i=1}^{N_{\mathrm{F}}} p_{i,n}^{(h)} = N,\ \forall h$. The transmit power is limited per hop, to enable a fair comparison with unipath routing. With the distance $d_{i,j}^{(h)}$ between node i and node j, the minimum possible distance $d_{\min}$ between two nodes and the path loss exponent α_{PL}, assuming $p_{i,n}^{(h)} = 1$ we define the normalized Signal-to-Noise Ratio (SNR) of the channel by

$$\gamma_{i,j,n}^{(h)} = \frac{1}{\sigma^2} \cdot \left(\frac{d_{i,j}^{(h)}}{d_{\min}} \right)^{\alpha_{\mathrm{PL}}} \cdot |H_{i,j,n}^{(h)}|^2. \tag{1}$$

The average SNR between node i and node j is given by

$$\bar{\gamma}_{i,j}^{(h)} = \frac{1}{N} \cdot \sum_{n=1}^{N} \gamma_{i,j,n}^{(h)}. \tag{2}$$

For a direct communication between two nodes, we assume that the SNR of the link between them has to be larger than or equal to $\bar{\gamma}_{\min}$, otherwise the link breaks. This means, a node j is considered to be out of the transmission range of node i if $\bar{\gamma}_{i,j}^{(h)} < \bar{\gamma}_{\min}$.

III. Corridor-based Routing

A. Assumptions

For the corridor construction and maintenance, physical layer information is taken into account. To obtain this information, the following assumptions are made.

1) Knowledge about neighbors: Similar to other protocols like AODV [2], we assume that nodes periodically broadcast hello messages to discover the neighborhood. We assume that the hello message of a node contains its identifier and a list of its 1-hop neighbors from which it has received a hello message. Thereby, each node discovers its 1-hop neighbors, as well as its 2-hop neighbors. Furthermore, we assume that each node uses the received hello message to estimate the actual average SNR to the transmitting node. We propose that this estimated average SNR concerning each 1-hop neighbor is then attached to the next hello message of the node. Thereby, each node monitors the link quality and the change of the link quality in its 2-hop-neighborhood.

2) Estimated link lifetime (LLT): Based on the estimated average SNR between two nodes, the distance between them can be estimated by

$$\hat{d} = d_{\min} \cdot (\bar{\gamma} \cdot \sigma^2)^{\frac{1}{\alpha_{\mathrm{PL}}}}. \tag{3}$$

By inserting the minimum SNR $\bar{\gamma}_{\min}$ in (3), the transmission range d_{range} of the nodes can be determined. To estimate the lifetime of a link, we use a similar approach as presented in [3]. The difference between two consecutive estimated SNR values indicates the tendency of link quality. In case that the latest estimated average SNR is smaller than the previously estimated average SNR, this indicates that nodes are moving away from each other. Based on the change of the estimated distance, we can determine the estimated LLT, i.e., the time till the distance exceeds the transmission range of the nodes by

$$t_{\mathrm{LLT}} = \frac{d_{\mathrm{range}} - \hat{d}_0}{\hat{d}_{-1} - \hat{d}_0} \cdot t_{\mathrm{Hello}}, \tag{4}$$

where $\hat{d}_0$ is the latest estimated distance, $\hat{d}_{-1}$ is the previously estimated distance and t_{Hello} is the hello interval, i.e., the time duration between two hello messages. In case that the SNR becomes larger, nodes are getting closer. Without knowing the exact positions or velocities of the nodes, it is not possible to determine the turning point at which the nodes will start to move away from each other which makes a reliable estimation of the LLT impossible. Therefore, we set the estimated LLT to ∞ as long as the trend of the SNR is positive.

B. Corridor construction

In the following, a corridor construction procedure is introduced which is based on [10]. We extend the construction by taking the estimated link lifetime into account to achieve a stable structure in dynamic networks. We assume that in each hop one master node is appointed which has the task to select the other forwarding nodes of its hop and to inform these nodes and the adjacent master nodes about this selection. If a link between adjacent master nodes would break, the required coordination could not take place anymore. Therefore, these links are necessary for the proposed operation of the corridor-based routing concept. For the resource allocation within each hop, which is discussed in Section III D, the forwarding nodes of a hop have to exchange channel information. Therefore, the links between them are also necessary for a successful operation. To build a stable corridor, the links between adjacent master nodes and the links between the forwarding nodes of each individual hop have to fulfill the following conditions concerning the estimated LLT and the link SNR:

$$\textbf{Condition 1}: \quad t_{\text{LLT}} \geq t_{\text{LLT,min}},$$
$$\textbf{Condition 2}: \quad \bar{\gamma} \geq \gamma_{\text{min}}^{\text{cor}}.$$

Condition 1 avoids links which are expected to break in a short time period. Condition 2 excludes node pairs connected by weak links with low SNR which are considered as not stable enough. In the following, the corridor construction is explained which is divided in two steps. Firstly, a unipath route has to be found and secondly, the unipath route is extended to a corridor.

1) Unipath route: To build the corridor, first we need to find a unipath route consisting of single nodes per hop from the source to the destination. In principle, every unipath routing protocol could be used as a basis for the corridor construction. However, many conventional routing schemes do not take into account physical layer information. They often aim at finding a path with a minimum number of hops by flooding the network with Route Request messages. Since this strategy can lead to weak, short-living links, we set a constraint concerning the link quality. To establish a stable unipath, only links are considered which fulfill Conditions 1 and 2. With this constraint, weak links can be avoided and the probability of long living links increases. Under this constraint, we determine a path with minimum possible number of hops.

2) Extension of unipath route to corridor: Initially, each node of the resulting unipath route is the master node of its hop. Each master node appoints up to $N_{\text{T,max}} - 1$ additional forwarding nodes for the hop, where $N_{\text{T,max}}$ denotes the maximum number of nodes per hop. Of course, this does not apply to the source and the destination. For the selection process, an algorithm is used which ensures that the links between all forwarding nodes of a certain hop fulfill Conditions 1 and 2. Out of all possible nodes, the nodes which provide the highest minimum SNR concerning the two adjacent master nodes are selected. Thereby, nodes are preferred which provide a good incoming and outgoing link quality. After the forwarding nodes of a hop are selected, the node which promises the highest minimum LLT concerning the adjacent master nodes is appointed as the master node of the hop. The proposed selection process is performed using Algorithm 1.

C. Corridor maintenance

When nodes are moving, the link quality between them changes or links can even break down. Instead of building a completely new corridor in case of link failures, we propose to locally maintain the corridor in fixed time intervals as long as the source still wants to transmit data. Due to the movement of the nodes, it can be useful to change the forwarding nodes of each hop, as well as the corresponding master node. In case that source and destination are coming closer to each other or moving away from each other, it may also be necessary to adapt the number of hops, i.e. cancel master nodes or appoint additional master nodes. Therefore, our proposed maintenance of the corridor includes an update concerning:

Algorithm 1 Select additional forwarding nodes

Require: link information (SNR + LLT) concerning 1- and 2-hop neighbors of master node in hop h
 for $h = 2$ to N_{H} **do**
  store master node of hop h in set of forwarders $\mathcal{S}_{\text{cor}}^{(h)}$ and store its 1-hop neighbors in set of candidates $\mathcal{S}^{(h)}$
  while $|\mathcal{S}_{\text{cor}}^{(h)}| < N_{\text{H,max}}$ and $\mathcal{S}^{(h)} \neq \{\}$ **do**
   1) for each node i of set $\mathcal{S}^{(h)}$ check LLT and SNR concerning each node in set $\mathcal{S}_{\text{cor}}^{(h)}$ and cancel node i from set $\mathcal{S}^{(h)}$ if Condition 1 or 2 is not fulfilled
   2) determine node i from set $\mathcal{S}^{(h)}$ with highest minimum SNR concerning adjacent master nodes, add it to set $\mathcal{S}_{\text{cor}}^{(h)}$ and cancel it from set $\mathcal{S}^{(h)}$
  end while
  store nodes of set $\mathcal{S}_{\text{cor}}^{(h)}$ which fulfill Condition 2 concerning adjacent master nodes in set $\mathcal{S}_{\text{cor}}^{(h)'}$
  determine node i out of set $\mathcal{S}_{\text{cor}}^{(h)'}$ with highest minimum LLT concerning adjacent master nodes and appoint this node as new master of hop h
 end for

1) the master node of each hop,
2) the number of hops in the corridor,
3) the forwarding nodes of each hop.

To deal with 1) and 2), Algorithm 2 is proposed. In this algorithm, the corridor is adapted hop-by-hop by each corresponding master node. The number of hops is reduced, stays the same or is extended depending on the current link situation. Based on the LLT and on the link SNR, the best suited new master nodes are selected. To avoid an excessive increase of hops during maintenance, the minimum SNR $\gamma_{\text{min}}^{\text{cor}}$ is replaced by $\gamma_{\text{min}}^{\text{cor}'}$ (with $\gamma_{\text{min}}^{\text{cor}'} < \gamma_{\text{min}}^{\text{cor}}$) which is referred to as Condition 2a. To adapt the forwarding nodes of each hop and thereby dealing with 3), Algorithm 1 is used afterwards.

D. Resource allocation

For the resource allocation in each hop, we assume that the forwarding nodes know about each others channel conditions concerning each subcarrier. This means, each forwarding node has to estimate its channel conditions and exchange this information locally to enable a common decision on the resource allocation. This means that the resource allocation is determined in a distributed way by each forwarding node of the current hop. The aim of the proposed resource allocation is to maximize the achievable data throughput in the corridor. We assume an exclusive subcarrier allocation in each hop which means for each subcarrier n, one transmitter-receiver pair has to be determined. The subcarrier allocation is indicated by the element $z_{i,j,n}^{(h)}$ which is equal to 1 if subcarrier n is allocated to transmit node i and receive node j and it is equal to 0 if this is not the case. The achievable throughput on each subcarrier is given by the channel capacity. The overall achievable throughput is given by

$$R_{\text{cor}} = \frac{1}{t_{\text{T}}} \sum_{j=1}^{N_{\text{R}}^{(1)}} \sum_{n=1}^{N} z_{1,j,n}^{(1)} \log_2 \left(1 + p_{1,n}^{(1)} \gamma_{1,j,n}^{(1)}\right), \tag{5}$$

Algorithm 2 Update corridor master nodes

Require: link information (SNR + LLT) concerning 1- and 2-hop neighbors of master node in hop h

for $h = 2$ to N_{H} **do**

  if link between master nodes of hop $h-1$ and $h+1$ fulfills Conditions 1 and 2 **then**

    cancel hop h

  else

    store all nodes which fulfill Conditions 1 and 2a concerning master nodes of hop $h-1$ and $h+1$ in set $\mathcal{S}^{(h)}$ (candidates)

    if $\mathcal{S}^{(h)} \neq \{\}$ **then**

      appoint node i out of set $\mathcal{S}^{(h)}$ with highest minimum SNR concerning the links to master nodes of hop $h-1$ and $h+1$ as new master of hop h

    else

      determine node pair i and j out of set $\mathcal{S}^{(h)}$ which fulfills Condition 1 and 2 for the links between: master node $h-1$ and node i, node i and node j, node j and master node $h+1$ and appoint the pair which provides the highest minimum SNR concerning these links as two new masters

    end if

  end if

end for

where the throughput achieved in the first hop is divided by the overall required transmission time $t_{\mathrm{T}} = \sum_{h=1}^{N_{\mathrm{H}}} t_{\mathrm{T}}^{(h)}$. The transmission time for the first hop $t_{\mathrm{T}}^{(1)}$ is assumed to be equal to 1. Since we assume a hop-by-hop transmission where the next hop does not start to transmit until all buffered data of the current hop is transmitted, the transmission time of the following hops is determined by the node which requires the longest time duration to forward all buffered data. Therefore, an iterative algorithm is proposed for the subcarrier allocation in each hop h in which first the transmit node i is determined which is allowed to select a subcarrier in the current iteration. This transmit node is determined based on the time $t_{\mathrm{T,i}}^{(h)}$ node i would require to transmit all buffered data using the subcarriers which are already allocated to node i in the current iteration. In the initial iterations, when no subcarrier is already allocated, the amount of buffered data decides which node is first authorized to select a subcarrier.

A selection of the subcarrier n and the corresponding receiver j only based on 1-hop SNR conditions could lead to undesired effects in situations as illustrated in Fig. 2. Due to the positions

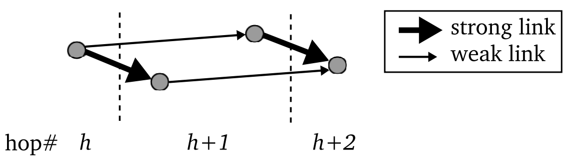

Fig. 2: Challenging node placement example.

of the nodes in Fig. 2, the incoming link of one node in hop $h+1$ is very strong and the node in hop h would probably allocate all subcarriers to this receiver. In this example, the weak outgoing link would significantly reduce the achievable throughput in the next hop. To avoid this effect, we take the average SNR of the outgoing links of each receiver into account which is known to each forwarding node based on the exchange of hello messages. To evaluate the channel condition of a certain subcarrier, we determine a 2-hop channel capacity, where it is assumed that the capacity of the second hop is given by $C_{j,\max}^{(h+1)} = \max_k \left(\log_2(1+\bar{\gamma}_{j,k}^{(h+1)})\right)$. We define the 2-hop channel capacity by

$$C_{i,j,n}^{(h)'} = \left(\frac{1}{C_{i,j,n}^{(h)}} + \frac{1}{C_{j,\max}^{(h+1)}}\right)^{-1}. \qquad (6)$$

The subcarrier allocation for hop h is described by Algorithm 3. After the subcarriers are allocated, each node applies water-filling [11] to determine the transmit power $p_{i,n}^{(h)}$ for each of its subcarrier.

Algorithm 3 Subcarrier allocation for hop h

Require: SNR per subcarrier and buffer level of each forwarding node of hop h and average SNR of hop $h+1$

store all subcarriers in set $\mathcal{S}_{\mathrm{sc}}^{(h)}$

while $\mathcal{S}_{\mathrm{sc}}^{(h)} \neq \{\}$ **do**

  determine transmit node i with $\max_i(t_{\mathrm{T},i})$ or max. buffer

  determine receiving node j and subcarrier n with $\max_{j,n}(C_{i,j,n}^{(h)'})$

  set $z_{i,j,n}^{(h)} = 1$ and cancel subcarrier n out of set $\mathcal{S}_{\mathrm{sc}}^{(h)}$

end while

IV. Performance Evaluation

In the following, the performance of the proposed corridor-based routing concept is evaluated and compared to shortest path routing (SPR). In SPR, a unipath route is determined consisting of the minimum possible number of hops. The system parameters are listed in Table I. The noise power σ^2 is chosen such that $\bar{\gamma}_{\min}$ is on average achieved for a distance of 100 m. To model the movements of the nodes, the Random Waypoint mobility model [1] is used assuming a pause time equal to 0, which means if a node reaches its waypoint, it starts moving to a new waypoint immediately. All results are averaged over 2000 independent Monte Carlo simulations.

First, we evaluate the performance of the corridor construction

TABLE I: System parameters

Map size	500m x 500m
Number of nodes	500
Maximum Node velocity	2 m/s
Hello interval t_{Hello}	2 s
Minimum SNR $\bar{\gamma}_{\min}$	5 dB
Number N of subcarriers	64
Minimum node distance $d_{\min}$	1 m
Pathloss coefficient α_{PL}	-3

scheme using a minimum LLT $t_{\mathrm{LLT,min}} = 30$ s (Condition 1) and a minimum SNR $\gamma_{\min}^{\mathrm{cor}} = 10$ dB (Condition 2). Fig. 3 depicts the average achieved throughput over time of CBR and SPR. In each simulation run, the corridor and the unipath are built once at the beginning and are not changed anymore during a given observation time of 60 s. It can be seen that the throughput achieved by SPR rapidly decreases over time. Since SPR aims at minimizing the number of hops, the resulting route consists of weak links which can break quickly due to the node movements. In contrast to this behavior, CBR provides a more stable structure. A link break which causes a transmission failure of the corridor usually first happens after a much longer time period compared to SPR. Therefore, the throughput is only slightly decreasing during the first 20 s. In the beginning, a gain of approximately 24 % is achieved compared to SPR. Due to the higher stability, this gain increases in the first 20 s. After this period, also the performance of CBR degrades since the probability of a link failure increases.

To avoid this performance degradation, the corridor maintenance proposed in Section III C can be used. For the corridor maintenance, a minimum SNR $\gamma_{\min}^{\text{cor}'} = 8$ dB (Condition 2a) is used. In Fig. 4, the achieved throughput of CBR with maintenance is compared to a resistant SPR. For the resistant SPR, it is assumed that in case of a link failure, a new unipath route is determined immediately. Therefore, the achieved throughput is constant during the considered time interval. The corridor is only maintained every 20 s which keeps the required overhead low. Note that the required overhead for route reconstruction is not taken into account in the performance of the resistant SPR. Nevertheless, it can be seen that CBR with maintenance can keep the throughput nearly constant without any unplanned reconstruction procedures. Although, the performance decreases during the 20 s between two maintenance steps, the maintenance leads to a recovery of the corridor structure which enables a comparable throughput as achieved in the beginning. Table II shows that the parameter $\gamma_{\min}^{\text{cor}}$ has only a marginal impact on the average throughput $\overline{R}_{\text{cor}}$ of CBR during the observation time which is caused by two opposing effects. By increasing $\gamma_{\min}^{\text{cor}}$ the links within the corridor become stronger which means that the channel capacity increases in each individual hop. However, also the average number of required hops increases which leads to a performance degradation. As can be seen, the highest average throughput is achieved for $\gamma_{\min}^{\text{cor}} = 10$ dB.

TABLE II: Impact of parameter $\gamma_{\min}^{\text{cor}}$ on the average throughput $\overline{R}_{\text{cor}}$.

$\gamma_{\min}^{\text{cor}}$ in dB	6	8	10	12
$\overline{R}_{\text{cor}}$ in bits/s/Hz	1.2633	1.3128	1.314	1.301

V. Conclusion

Corridor-based routing enables diversity gains for wireless multihop transmissions by widening a unipath route to a support structure consisting of multiple forwarding nodes in each hop. In this work, we extend the corridor construction by taking physical layer information in terms of estimated LLT into account. Furthermore, a concept for corridor maintenance is introduced which can adapt the corridor to changes of the network caused by node movements. In addition, we propose a novel resource allocation scheme considering 2-hop average link quality to avoid bottlenecks during the multihop transmission. Thereby, corridors can be constructed which provide high throughput gains and higher stability compared to conventional shortest path routing. By maintaining the corridor in large time intervals, the performance stays nearly constant without any undesirable reconstruction procedures.

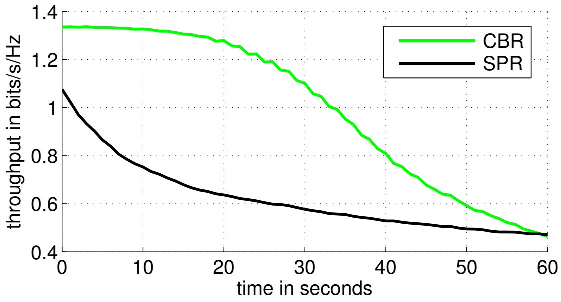

Fig. 3: Average throughput vs. time.

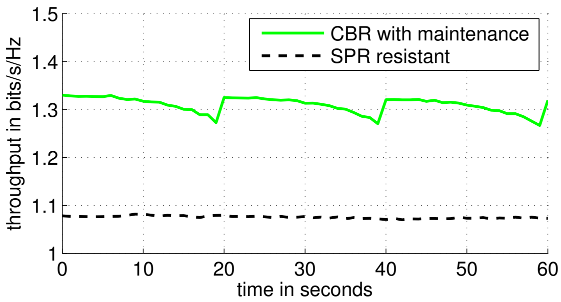

Fig. 4: Average throughput vs. time.

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