Low-Complexity Beamforming Techniques for Wireless Multi-hop Networks

Robert Vilzmann[1] , Jörg Widmer[2] , Imad Aad[2] , and Christian Hartmann[1]
[1] Technische Universität München, Institute of Communication Networks, Munich, Germany
[2] DoCoMo Euro-Labs, Future Networking Lab, Munich, Germany

***Abstract*— Protocols for beam-forming antennas usually direct the beam toward the respective communication partner. This requires significant coordination between nodes and results in frequent changes of the beam direction. In this paper, we present much simpler algorithms that instead aim at improving the network topology to enhance connectivity and robustness of routing. A node computes the optimal beam direction using aggregate information about its neighborhood such as the number of neighbors in each beam direction. We analyze the performance of such algorithms in terms of number of paths to a destination, mutual interference, and route lifetime in mobile networks and show that they are a promising alternative to existing beamforming schemes.**

***Index Terms*— Multihop networks, beamforming, adaptive antennas, multipath routing.**

I. Introduction

Using beam-antennas has proven to be a promising technique for wireless devices. Devices with a beam antenna may radiate power in a specific direction instead of omni-directionally, which may positively affect the network in terms of connectivity, hop distances, interference, etc. These improvements usually come at the cost of increased protocol and hardware complexity.

There are two known approaches for selecting the beamforming direction with very different complexity, namely (1) Random Direction Beamforming (RDB), and (2) Communication-based Beamforming. While the first solution is very simple, its performance remains limited compared to communication-based beamforming. Nevertheless, it provides significant performance gains over omnidirectional antennas. In contrast, the second class of solutions considerably increases the system performance, at the cost of high complexity. It involves choosing the direction of the beam per packet or per connection based on information about the location of the destination of the transmission.

This paper improves upon RDB, while avoiding the complexity of communication-based beamforming. The proposed algorithms select the beamforming direction based on aggregate information collected from neighboring nodes. In particular, we investigate schemes that adapt the beamforming direction with respect to the number of neighbors found in specific directions. This information is gathered by the nodes through occasional sweeps over all possible antenna directions. The proposed schemes have reasonably low algorithm and signal processing complexity and allow for using standard MAC and routing protocols not specifically adapted to dynamic beamforming.

The performance analysis of these algorithms covers several aspects. First, network connectivity as well as availability of node-disjoint paths is analyzed. Second, convergence behavior of the algorithms is studied for static networks. We further investigate the amount of coupling between these multiple paths. Finally, we look at mobile scenarios and assess to what extent fixed beamforming can be used when nodes are mobile. From this analysis, it becomes apparent that rotation-aware modeling of mobility is critical in the simulation of mobile multihop networks. The modeling approach concerning the antenna and beamforming model, the link model and the network scenario follow the ones proposed in [1], [2].

The paper is organized as follows. In the next section we discuss existing approaches for selecting a beamforming direction. Section III gives an overview of the proposed algorithms for beamforming based on aggregate neighborhood information. Section IV describes the modeling of the antenna array and other simulation aspects for static scenarios. The performance analysis of the static scenarios is then given in Section V. Correspondingly, Sections VI and VII describe models and simulation results for mobile scenarios. We conclude the paper with Section VIII.

II. Related Work

Considerable work on directional antennas in ad hoc networks can be found in the literature. To better position our work with respect to those, we sort existing work into two groups: Communication-based beamforming [3]–[19] and random direction beamforming [1], [20], [21].

The first group of protocols considerably increases the system performance, at the cost of high complexity. Nodes either detect the angle of arrival of the signal from a given neighbor [4], [16] or they just maintain a location table to keep track of beam directions to every neighbor [3], [15]. To help localizing their neighbors, nodes exchange RTS/CTS messages [3]–[7], [12], use new handshake mechanisms [10], [13], or just transmit/receive tones [11], [14], [16]. These protocols define different combinations of omni/directional transmissions of handshake messages or tones, trying to solve the hidden node, exposed node, and deaf node problems. A survey of those protocols can be found in [22].

All of these communication-based beamforming require that nodes continuously search and adapt to the position of their communication partner, which requires tight coordination between nodes, resulting in high complexity and overhead.

The main idea in random direction beamforming [1], [20], [21] is to let nodes direct their beams in random directions, regardless of the positions of communicating nodes, the network topology, or angles of arrival. Clearly, this reduces communication overhead and algorithm/hardware complexity. The authors show how random beamforming outperforms omnidirectional transmissions in terms of interference reduction, number of hops, delays etc., without the complexity and overhead of communication-based beamforming. While those protocols are simple their performance remains limited: when nodes close to the border of the network or next to an obstacle beamform in a direction where they have no neighbors they become isolated from the rest of the network.

Compared to existing solutions, our solution is situated in between random direction beamforming and communication-based beamforming. The algorithms we propose in this paper are much less complex than communication-based beamforming since they require no coordination among nodes, while significantly outperforming random beamforming direction at a comparable complexity.

III. Algorithms

Random Direction Beamforming (RDB) [1], [20], [21] improves topology properties compared to omnidirectional antennas without introducing additional dynamics at the MAC layer, since the beamforming is static. The improvement, for example, in connectivity can nicely be seen in Fig. 1(a) and Fig. 1(b). Furthermore, RDB does not need direction of arrival estimation or adaptive adjustment of antenna steering vectors. In this section, we assess alternative schemes with the same advantages, but which outperform RDB in terms of topological properties. Here, a node computes the optimal beam direction using aggregate information about its neighborhood such as the number of neighbors in each beam direction.

In the simplest case, status information to compute a beam direction can be gathered at each node independently from other nodes (e.g. by overhearing ongoing transmissions). Alternatively, it can be disseminated using periodic beacon messages, which allows nodes to include higher level information (e.g. the node's energy level, its number of neighbors, etc.).[1] The more knowledge a node has about the network, the higher the improvement it can achieve by directing its beam-antenna. However, complexity and overhead costs increase when information flows over several hops in the network.

A. Maximum Node Degree Beamforming (MNDB)

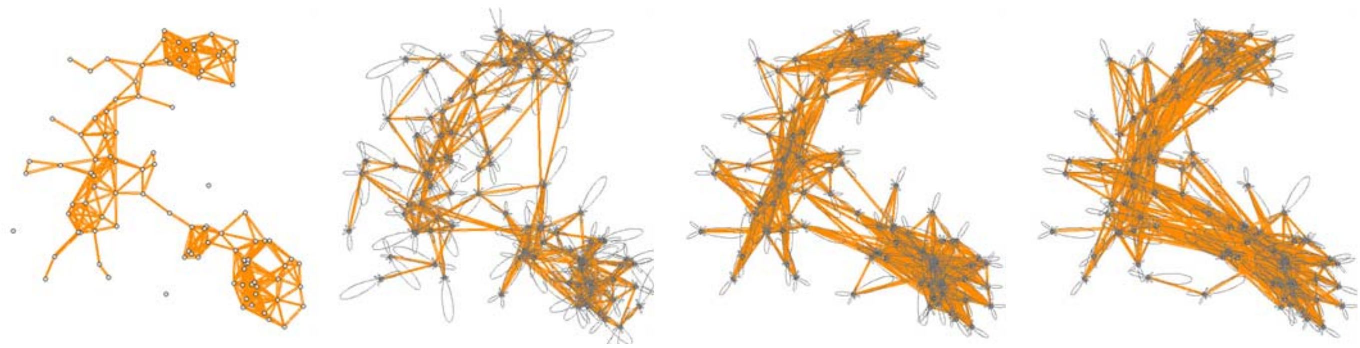
A first advanced scheme which we propose fixes the beamforming in a direction where the number of neighbors is maximum. In order to achieve this, we consider a scheme that is based on sweeping the main lobe of the antenna beam pattern. For a given main lobe direction, the node determines the node degree, for instance by counting the number of received beacons.

A mobile terminal initially beamforms in a random direction (as with RDB). From time to time, a node sweeps the main lobe by incrementing the beamforming angle by a predefined amount β.[2] Each angle direction is kept for a certain time period, during which the node overhears the neighbors' transmissions of data packets and also of beacons, in case dedicated beacon messages are used. Upon completing a full sweep of $360°$, the node beamforms in the direction where the node degree was maximum (i.e., the highest number of distinct MAC layer source addresses was seen). If this maximum node degree occurred in more than one direction, one of these directions is picked at random. We refer to this scheme as Maximum Node Degree Beamforming (MNDB).

The sweeping is carried out by each node individually and uncoordinated with other nodes. In case the network topology remains static, the beam directions will usually converge after a few iterations.

[1] Beacons are sent using the current beam configuration without changing the beam direction.

[2] For the simulations, β was set to $10°$.



(a) No beamforming (OMNI) (b) Random Direction Beamforming (RDB) (c) Maximum Node Degree Beamforming (MNDB) (d) 2-Hop Node Degree Beamforming (TNDB)

Fig. 1. Sample topologies resulting from the different beamforming approaches, for $n = 100$ nodes with inhomogeneous (clustered) node distribution. In general, beamforming provides better connectivity than omni-directional antennas. Further information about the neighborhood can be used to significantly improve the resulting topology as evidenced for MNDB (one-hop information) and TNDB (two-hop information).

As can be seen from Fig. 1(c), MNDB completely eliminates the problem of border nodes having very few neighbors because they beamform away from the network. Also the average number of neighbors per node increases significantly, which will be analyzed in more detail in the simulation section.

B. Two-hop Node Degree Beamforming (TNDB)

In some non-homogeneous topologies, MNDB can result in sub-optimal connectivity, where nodes point their beams such that they form clusters with strong connectivity within each of them, but few connections between different clusters. This effect is depicted in Fig. 1(c). To overcome this problem, nodes can use the 2-Hop Node Degree Beamforming algorithm (TNDB) to maximize the number of distinct one- and two-hop neighbors.

Here, the status updates contain a list of distinct overheard MAC source addresses of a node. This list may be too large to be piggyback onto data packets and will typically be disseminated with dedicated beacons. From this information, each node calculates the number of distinct MAC addresses of the two-hop neighborhood, by merging all available lists and removing duplicate addresses.

By maximizing the number of two-hop neighbors, nodes are more likely to connect clusters of nodes. Intuitively, if a node is at the border of a cluster with strong internal connectivity, it will remain connected to the cluster through its antenna side lobes (see Fig. 2), even if the main lobe does not point toward the cluster. As a consequence, instead of directly being connected to all of the cluster nodes, the node will only be connected to a few neighbors very close by, but they in turn will provide connectivity to the rest of the cluster. If the main beam is then set in the direction of a different cluster that can only be reached by directly pointing to beam at the ideal angle toward that cluster, the node gains a large number of further two-hop neighbors in the new cluster, while losing few neighbors in the old cluster. This can clearly be seen in Fig. 1(d), where connectivity between cluster is almost as strong as connectivity within the individual clusters.

C. Implementation Considerations

The step size β and step duration for the sweeping can both be adapted to obtain a statistically significant sample of the status updates in the corresponding direction. The number of updates (be they through overheard packets or dedicated beacons) over time determines the speed with which the sweeping can occur. In case data packets are sent very frequently, it may be sufficient to piggyback status information only onto some of them. In contrast, if very little or no traffic occurs, inferring an accurate image of the topology might take too much time without using dedicated beacon messages. The beacon frequency can be adapted such that the total number of updates a node can overhear per time step remains relatively constant.

A threshold parameter determines when a change in neighborhood information is considered significant enough to actually change the beam direction. The lower the threshold, the closer beam direction tracks the optimum direction. On the other hand, frequent changes in beam direction have a negative impact on the stability of the network. Changing the beam direction results in changes to the parameter values of the neighbors and this can cause them to also change their beam direction in turn, when they do their next sweep. In this case, a wireless routing algorithm that is running on top of the proposed beam forming protocol would have to frequently adjust to the changes in the neighborhood, computing new routes and tearing down invalid old ones. Therefore, it is important to adapt the threshold parameter to the responsiveness of the routing protocol, network parameters such as node mobility, as well as requirements concerning connectivity, availability of alternate paths, etc.

This intelligent adjustment can be done through additional signaling between the beam direction protocol and higher layers such as the routing or even application layer. A higher layer may change the threshold (as well as the other parameters of the algorithm) in case it detects that the network is too unstable. It may also indicate that the network is considered stable enough such that a threshold decrease would be acceptable.

IV. Network model

This section briefly summarizes the models that were used for the analysis presented later. For a more detailed description see [20].

A. Node placement

In the beginning of each simulation run, a specified number n of nodes is placed randomly and independently in the simulation area $\mathbf{A}$ of size $1000 \times 1000\,\mathrm{m}^2$. Two different scenarios are investigated, a

- homogeneous node distribution and an
- inhomogeneous, clustered node distribution.

In the first case, the node positions are randomly chosen in $\mathbf{A}$ according to a uniform distribution. In order to generate the inhomogeneous scenario, we first determine five cluster centers in the simulation area, which are also randomly chosen in $\mathbf{A}$ from a uniform spatial distribution. In a second step, the total number of nodes is split evenly among the clusters. Finally, the positions of nodes belonging to each cluster are chosen according to a two-dimensional Gaussian distribution whose mean value is determined by the position of the respective cluster center. The standard deviation of all Gaussian distributions is chosen as 10% of the system area width.

B. Channel and link model

We assume that all nodes are transmitting with the same fixed transmit power p_t and that all nodes have the same receiver sensitivity p_{r0}, which is the minimum power a node must receive in order to decode data correctly. Therefore, a link can be established between two nodes if the overall path gain a_p is above a threshold value defined as $a_{po} = p_{r0}/p_t$. The overall path gain a_p is computed as follows:

$$a_p = g_t \cdot g_r \cdot g_c(d) \ , \tag{1}$$

where g_t is the transmit antenna gain in the direction from the sending node to the destination, g_r is the receive antenna gain in the direction from the receiving node to the source, and $g_c(d) = 1/l_c(d)$ is the reciprocal of the pathloss $l_c(d)$, which is a function of the distance d between the two nodes. To describe $l_c(d)$, we apply the modified free space path loss model with attenuation exponent $\alpha = 3$. The received power at a node from a sending node is consequently determined as $p_r = p_t \cdot a_p$, regardless whether the sending node is the current communication partner or an interferer. The following section describes how the required values for g_t and g_r are obtained.

C. Antenna and beam steering model

We assume that nodes which are capable of beamforming are each equipped with an 10-element *uniform circular array* (UCA10), i.e. 10 antenna elements are placed on a circle, such that the distance between two neighboring elements is Δ. We choose $\Delta = \lambda/2$, where λ is the wavelength of the carrier. Each single antenna element is modeled as an isotropic radiator. Applying the described UCA, we perform directional beamforming by means of phase shifting: The transmit power p_t is evenly split among the single elements, such that each element transmits with power $p_t/10$. However, the phase of the signal transmitted by an element is shifted by a tunable value γ relative to the preceding element. Given a beamforming direction with respect to the array orientation, we choose γ such that the antenna gain is maximized in the desired direction. The resulting pattern is characterized by a strong main lobe and some smaller side lobes. The specific shape of the pattern, most importantly the shape of the side lobes, depends on the beamforming direction relative to the array orientation. Depending on the array orientation, the pattern specified by the choice of γ can point its main beam in any

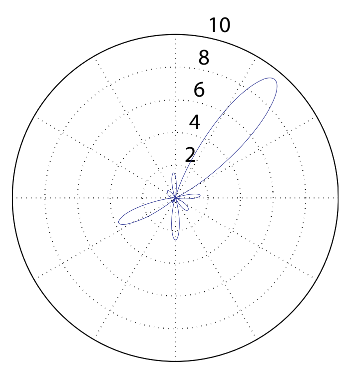


Fig. 2. Example gain pattern for a uniform circular array with 10 elements

direction in the simulation scenario. Therefore, given an array orientation and a value γ, the antenna pattern of a node defines the transmit antenna gain g_t as well as the receive antenna gain g_r in each angular direction.[3]

V. Analysis and simulation results

In multi-hop networks, a major criterion for the performance of communication is network connectivity (i.e., the probability that a path between two random nodes exists) and the average hop length of routing paths. In this section we investigate how the proposed algorithms perform with respects to these metrics.

Also path diversity is an important topological property. When a currently used path breaks, available alternative paths can substitute for this, and thus prolong the route life time. The route life time is defined as the time period between discovering multiple paths and the breakage of the last of these paths. On the network layer, this presumes a multi-path-aware routing protocol. Besides increasing the route life time, multi-path routes can also be used for load balancing in meshed networks. In this case, the burden of forwarding data traffic is split among the nodes of the utilized paths.

In wireless multi-hop networks, disjoint multi-path routes usually refer to *node-disjoint* paths. This is because link breaks are primarily due to node failures, node switch-offs and node movement. This is in contrast to wired networks with highly available network nodes, where path breaks are primarily due to link outage (fiber cut).

Multiple paths between two mobile nodes do not have to be completely node-disjoint. Previous work showed that a partial protection of paths already improves the route life time significantly [23]. Furthermore, the protection of short paths by very long paths has been shown to result in an only minor extension of the route life time [24]. This is because a long path, i.e. a path with many forwarding nodes, breaks with high probability before a short path does. Despite these facts, fully node-disjoint paths are considered in this work, since they can be analyzed more systematically. Furthermore, partially node-disjoint paths comprise at least one fully node-disjoint portion of the path, which is again subject to our analysis.

When determining multiple paths, the weight for all links is equal to one. This means that the path metric is simply the hop count. Since the focus of this work is on topology properties rather than on protocol behavior, an ideal path discovery using the Dijkstra algorithm is assumed.

The approach is as follows. First, the shortest path between the two nodes under consideration is determined. All forwarding nodes of the first path are removed from the topology graph, and the Dijkstra algorithm is run again for determining the second path. These two steps are repeated until no further path between the source and the sink exists. In case of a direct link between source and sink, the first path is a single-hop path, and the direct link is removed before determining the second path.

This approach of removing nodes from the graph does not result in what is referred to as *k-shortest paths* in graph theory. We decided not to analyze k-shortest paths, since wireless multi-path routing protocols usually discover routes including the shortest path. This is because successive determination of shortest paths is more practical for ad hoc routing protocols than determining k-shortest paths.

A. Connectivity and node-disjoint paths with RDB, MNDB and TNDB

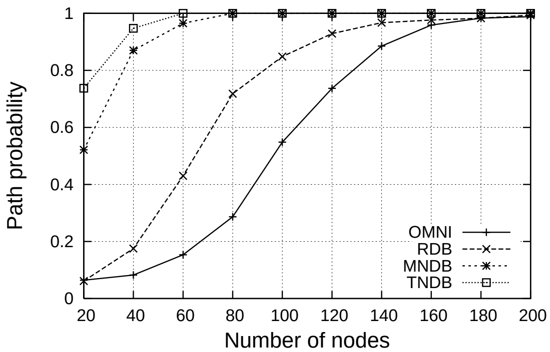
All results in this section are averages over 50 topologies. For each topology, node-disjoint paths were determined for all possible node pairs. Thus, in the case of the scenario with 100 nodes, the results are based on 247,500 node pairs.

For comparing the different schemes, we first analyze the connectivity of the network. The measure for connectivity is the path probability, which is estimated by the percentage of connected node pairs. Second, we analyze the number of node-disjoint paths which is available on average. The analysis is carried out both for scenarios with homogeneous node distributions and for clustered topologies. The impact of the node density is studied by varying the number of nodes on a fixed-size system area of $1000{\times}1000\,\mathrm{m}^2$. Fig. 3 summarizes the results for connectivity and availability of node-disjoint paths.

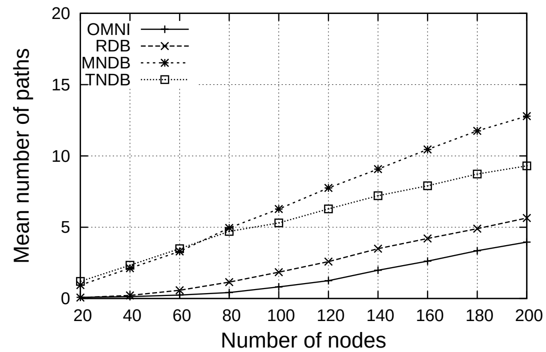
The simple RDB beamforming scheme leads to a better connected network when compared to omni-directional antennas (Fig. 3(a)), as already reported in previous work [20]. In clustered scenarios, the benefit of RDB lies in the fact that connections between clusters occur even without coordination between nodes. This leads to a significant improvement even when the number of nodes in the system area is already high.

As expected, MNDB outperforms RDB in terms of connectivity, most importantly when the node density is low. This is mostly because nodes close to the system area border do not beamform away from the network, as

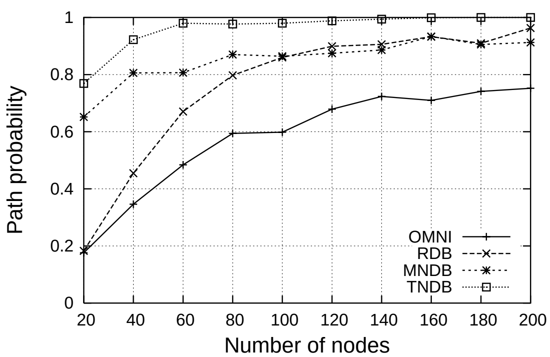
[3] In the reception case, the signal received at the single antenna elements is phase shifted according to γ and then combined, yielding the same directional gain pattern shape as resulting from the transmit beamforming.



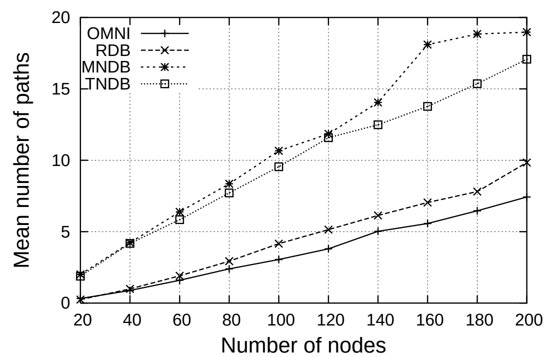
(a) Path probability with homogeneous node distribution



(b) Mean number of paths with homogeneous node distribution



(c) Path probability with clustered node distribution



(d) Mean number of paths with clustered node distribution

Fig. 3. Estimated means for the path probability and the number of node-disjoint paths between two randomly chosen nodes on $1000 \times 1000\,\mathrm{m}^2$.

is possible in the case of RDB. However, with inhomogeneous node distributions, MNDB tends to form clustered topologies. As a result, the path probability does not improve over the RDB case when the network comprises many nodes (Fig. 3(c)). Comparing Fig. 3(c) to Fig. 3(a), using OMNI and RDB, the network is better connected with a clustered distribution than with a homogeneous one. This is due to the fact that with a low number of nodes homogeneously distributed, a node would rarely find neighbors within its communication range. However, in a clustered topology, a node has a higher chance to connect to neighbors, and occasionally to its chosen destination node. This effect is less pronounced with MNDB or TNDB, since they already show much better connectivity even with low node densities.

The best connectivity in all cases can be achieved by exploiting two-hop information, using TNDB. It is most advantageous in increasing the path probability in the clustered case.

The average number of available node-disjoint paths with beamforming is significantly higher with MNDB than with RDB, as apparent from Figs. 3(b) and 3(d). With respect to the number of node-disjoint paths, MNDB is the preferred beamforming scheme when looking at average values. When looking at the distribution of the number of node-disjoint paths (numerical results are excluded for the sake of clarity), however, TNDB shows a slightly higher percentile of node pairs having a moderate number of paths. Having a high percentage of nodes with some backup paths may be more desirable than a high average number of paths. Thus, in summary, TNDB can be regarded as the best-performing beamforming scheme among the proposed approaches.

B. Path length distribution

The previous section showed that the proposed low-complexity schemes provide mobile nodes with a higher number of node-disjoint paths between them. In this section, we investigate the length of these paths. Short paths are desirable due to several reasons. For instance, shorter paths lead to less delay in multihop transmissions, a smaller number of involved forwarding nodes, and more stable and thus more reliable routes.

The mean number of paths for a given path length is depicted in Fig. 4, comparing omnidirectional antennas with RDB, MNDB, and TNDB, respectively. We limit the results to a scenario with $n = 100$ nodes. A path length of 1 represents a direct link (singlehop).

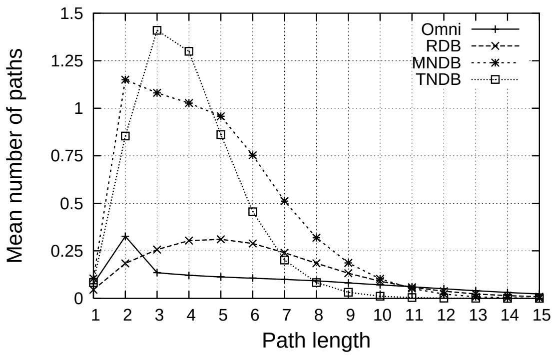


Fig. 4. Mean number of paths for a given path length, for 100 nodes on $1000 \times 1000\,\mathrm{m}^2$.

The highest number of "useful", i.e. short paths can be obtained with TNDB. The distribution is more spread out with MNDB, but the paths are still rather short. Generally, the less "sophisticated" the approach, the higher the number of very long paths, which are less desirable due to the above-mentioned reasons. The maximum for omnidirectional antennas is at a path length of 2. However, not performing beamforming at all leads to a general lack of paths.

C. Convergence of MNDB and TNDB

Convergence of the proposed iterative schemes is critical. Weak convergence would lead to large overhead, since the number of neighbors would have to be determined often. If a scheme does not converge at all, nodes would have to re-adjust the beamforming repeatedly even though the node locations remain unchanged.

With MNDB and TNDB, the beamforming direction is only changed if this leads to a change of the node degree. (There is no random picking of a suitable beamforming direction when the metric does not change.) Otherwise, in particular when β is small, the nodes would re-adjust the beamforming direction with high probability even though the node degree metric does not change.

In order to assess the convergence behavior, the above-mentioned performance metrics are analyzed after each iteration. An *iteration* denotes the re-adjustment of the main lobe direction, done by each node. Average values are gathered over 50 topologies with 100 nodes. The results are shown in Fig. 5.

Both the MNDB and the TNDB schemes show good convergence behavior, and the performance metrics are stable after only few iterations. Moreover, the benefits of these iterative schemes would be largely achieved even if limited to only one iteration.

Interestingly, for MNDB with inhomogeneous (clustered) node distributions, further iterations after the first one slightly reduce the path probability and the average number of node-disjoint paths. This is due to a tighter clustering after continued re-adjustment of the main lobe towards locations with high node density. In contrast, TNDB profits from further iterations.

D. Analysis of Coupling

Not only the number of available node disjoint paths is of interest, but also the mutual interference that occurs when they are used simultaneously. This mutual interference has in previous work been referred to as *coupling*.

In this section, we analyze the amount of interference between paths when omni-directional antennas, RDB, MNDB, and TNDB are deployed, respectively. We carry out a worst case analysis, since there is no clear definition of coupling. Worst case means that all forwarding nodes of the parallel paths are assumed to transmit simultaneously when assessing the interference level prevailing at a given node, without assuming any medium access control functionality.

We analyzed a scenario with 50 nodes on $500 \times 500\,\mathrm{m}$. For each node that is a forwarding node on one of the paths of a multihop route, the interference power of all remaining nodes is added up. Interference of other nodes or routes is not considered. A detailed discussion of interference in multihop networks with our antenna and beamforming model, not being restricted to node-disjoint paths, is given in [2].

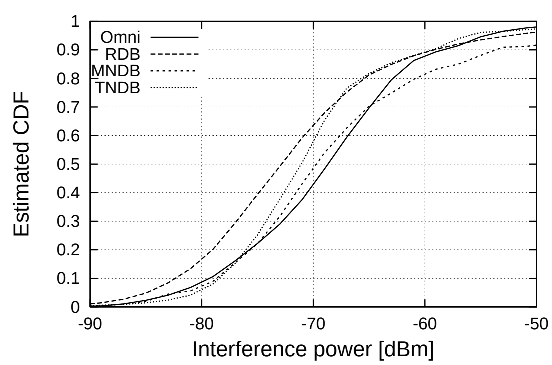
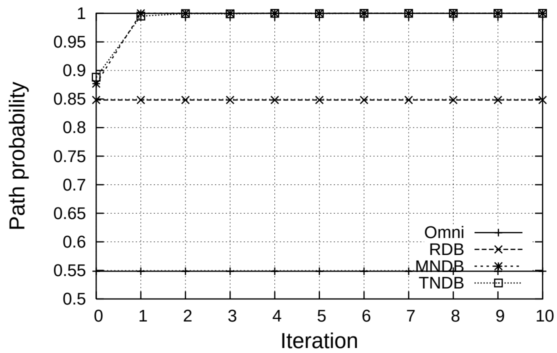
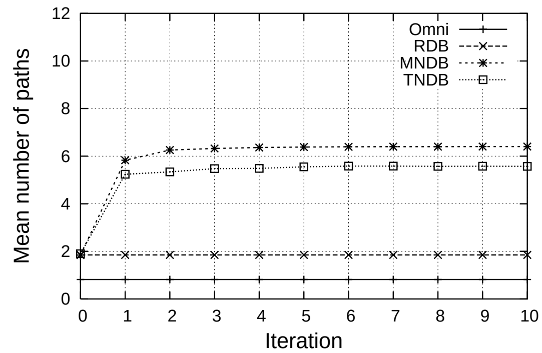


Fig. 6. Cross-interference between paths of multi-path routes consisting of four paths: worst case analysis

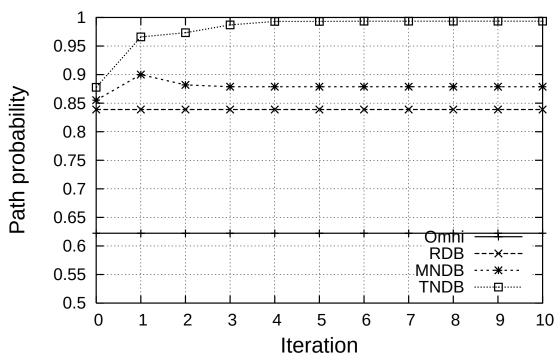
Only routes consisting of a fixed number of paths are considered in the results, so as to provide a fair



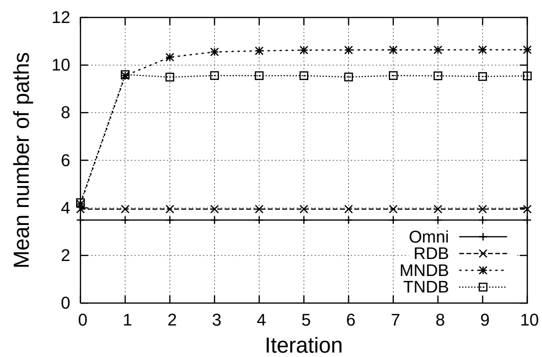
(a) Homogeneous node distribution



(b) Homogeneous node distribution



(c) Clustered node distribution



(d) Clustered node distribution

Fig. 5. Path probability and number of node disjoint paths for $n = 100$ nodes on $1000 \times 1000\,\mathrm{m}^2$ with different location distributions

comparison of the different schemes. Fig. 6 shows results for multi-path routes with four paths. The interference distribution is estimated by a histogram with a bin width of $2\,$dBm.

Looking at the 80% percentile in the interference distribution, the amount of interference between four paths is reduced by about 2.9 dB by RDB as compared to omnidirectional antennas. TNDB yields similar interference with respect to high interference levels beyond $-70\,$dBm. MNDB leads to increased interference between paths. For interference levels beyond $-65\,$dBm, MNDB shows the highest probability among all investigated schemes.

VI. Modeling mobility with directional antennas

In the following section, our proposed MNDB scheme is analyzed in a mobile scenario. The modeling of mobility has received ample attention in the research community. However, mobility modeling is usually limited to translatory motion. In our work, we model the fact that nodes rotate when the direction of translatory motion changes. Even if the rotation is compensated by adjusting the antenna beam (beam steering), the entire gain pattern changes due to re-adjusting the steering vector. In general, this also applies to beam switching antennas, if predefined antenna patterns are generated electronically.

Fig. 7 illustrates both the case of not modeling rotation (left-hand side), and the case of considering rotation (right-hand side). When accounting for rotation, steering the beam into the intended direction keeps the main lobe aligned, but the side lobe pattern changes significantly.

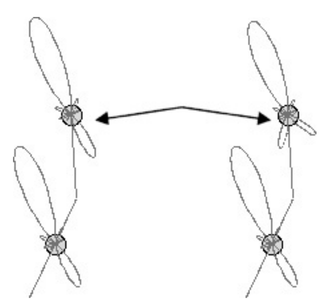


Fig. 7. Beamforming patterns (for mobile device equipped with UCA10 antenna) before and after change in direction of motion, without (left) and with (right) modeling of rotation

Modeling this additional degree of freedom for motion in ad hoc networks has, to the best of our knowledge, not been addressed before. Section VII-C exemplifies the significant impact of not modeling such rotation in computer experiments.

Besides modeling rotation that is due to changes in direction, intrinsic rotation of the mobile device without translatory motion might also be modeled. In particular, hand-held devices could be modeled more realistically in this manner.

VII. Low-complexity beamforming in mobile scenarios

All previous sections were concerned with static scenarios. A major caveat against beamforming schemes not being communication-based is the question whether such “fixed” beamforming can perform well in mobile scenarios. Intuition suggests that a directional antenna gain leads to failure-prone links when nodes move independently of each other. This section quantifies the life time of routes, comparing the usage of omnidirectional and directional antennas.

The same modeling approaches as in previous sections are assumed. Routing protocols are not regarded in the analysis. It is assumed that all node-disjoint paths between the node pair under consideration have been determined before nodes start to move. For assessing the route life time, all possible node pairs in the scenario are considered, and probability distributions for the route life time are estimated by means of simulations. In the case of directional antennas, Maximum Node Degree Beamforming (MNDB) is deployed throughout this section.

Routes break due to changes in attenuation, which is caused by node mobility. The random direction mobility model is used due to its ergodic characteristics. Nodes reaching the system area border are bounced back. The maximum speed of mobile terminals is set to $5\,\mathrm{km/h}$. The mobility model is rotation-aware as described in section VI.

A. Route life time with MNDB

Reference is now made to Fig. 8, showing the percentage of routes remaining after a given time elapsed. In the beamforming case, areal shearing effects due to the directional antenna characteristics lead to rapid path breaks. Consequently, the distribution of the route life time plunges down even though the speed of the mobile terminals is relatively low (see curve for “no rotation compensation”). After about $11\,\mathrm{s}$, a lower percentage of established routes remains in the beamforming case, as compared to using omnidirectional antennas.

Besides the life time of routes, we also analyzed the life time of the shortest path, which is usually the preferred path if only one path is used for communication. The corresponding distribution of the shortest path, which does not necessarily break first, shows a similar behavior as the distribution for the entire route. The analysis of the shortest path is therefore excluded for the sake of clarity.

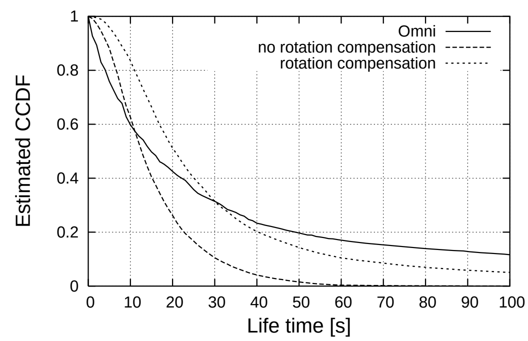


Fig. 8. Route life time with random direction mobility model for 100 nodes on $1000 \times 1000\,\mathrm{m}^2$.

B. Improving route life time by beam tracking

In this section, an adaptation of static beamforming is proposed, seeking to facilitate its usage in mobile scenarios. The aim is to increase the route life time by compensating for motion. While the proposed scheme is still static in the sense that the beamforming pattern is not responsive to traffic or interference, nodes now continuously adapt the relative main lobe direction over time.

In particular, nodes try to cover the same transmission area as they did when the node-disjoint paths were established. In order to achieve this, each node performs *beam tracking* (“rotation compensation”), and thus compensates for rotation by re-adjusting the direction of the main lobe. It is assumed that each node has full knowledge about its orientation, and can thus re-adjust its beamforming pattern upon motion so as to maintain the absolute direction of the main lobe.

As Fig. 8 shows, beamforming in combination with beam tracking improves the route stability for up to about $30\,\mathrm{s}$ over omnidirectional antennas. In this time span, nodes cover only a small distance from their starting point, and the route stability benefits from the higher number of paths provided by beamforming. Beyond this time span, the route life time distribution falls below the distribution for omnidirectional antennas.

C. Importance of rotation-aware mobility models

The mobility model used in this work accounts for rotation of the antenna array when the direction of motion changes. Even if this rotation is compensated by ideal main lobe steering, the side lobe pattern of the multi-element antenna changes quite drastically. If the mobility model would not be rotation-aware (corresponding to the left-hand side of Fig. 7), the results for the route life time would be too optimistic. Our results showed that, with this flaw in modeling motion, the enhanced beamforming scheme would outperform omnidirectional for time spans up to about $100\,\mathrm{s}$. With proper modeling of rotation, this is the case only up to about $30\,\mathrm{s}$.

VIII. Conclusions and Future Work

In this paper we propose simple, low-complexity beamforming techniques for ad hoc networks, MNDB (Maximum Node Degree Beamforming) and TNDB (Two-hop Node Degree Beamforming). Both techniques use aggregate information about a node's neighborhood for setting its beam direction. Compared to using omnidirectional antennas and random direction beamforming, both MNDB and TNDB provide better network connectivity, shorter paths (therefore reducing end-to-end delays), and lower interference. On the other hand, MNDB and TNDB require considerably less complexity than communication-based beamforming.

For future work we consider improving these algorithms by using additional information from neighbor nodes such as available energy, congestion level, and channel quality. For instance, pointing the beam to an area with high node density is sub-optimal if the nodes in the area have low energy levels. Including energy levels in the transmitted information would allow to increase network lifetime and reduces the cost of operating the network.

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