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Interference-based routing in multi-hop wireless infrastructures

Geert Heijenk *, Fei Liu

Department of Computer Science, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

Abstract

In this paper, multi-hop wireless infrastructures are identified as a way to increase user data rates and/or capacity of wireless systems by means of a high base station density without high base station interconnection costs. For such a system, a new routing algorithm, named balanced interference routing algorithm (BIRA), is proposed. One of the main features of this new routing algorithm is to take the interference between wirelessly transmitting nodes into account. In BIRA, a link cost is calculated considering the interference level of a node and a fixed cost for each link. Based on this link cost, the Dijkstra algorithm is used to compute routes. This article introduces BIRA and presents a performance analysis, both for the case where data are flowing in two directions to and from the fixed network, and for the case where data are only flowing in the direction of the fixed network. From the performance analysis, we see that BIRA outperforms other algorithms in terms of obtained data rates for a given available spectrum. BIRA helps to reduce the interference in the network and to achieve higher throughput.

Keywords: Interference; Routing; Wireless; Cross-layer optimization; Mesh network

1. Introduction

In order to increase the capacity of cellular communication systems, future generation systems may need to locate base stations much closer together compared to second and third generation cellular systems. Doing so may result in increased frequency reuse and increased data rates and/or capacity. Such a scenario will lead to a very high density of base stations, which will not be all connected to a wired infrastructure, for cost reasons. This will lead to a situation, where data from wireless terminals, such as cellular phones, portable or wearable computers, and sensors, are not transferred to and from the wired infrastructure in a single hop. Since a significant number of base stations do not have a wired connection, they merely serve as a relay, resulting in a situation where most of the data are transferred to and from the wired infrastructure in multiple hops. This leads to a network with: (1) base stations connected to the wired infrastructure; (2) stationary relaying base stations without a connection to the wired infrastructure; (3) terminals (mobile devices generating and absorbing data). Note that this type of system is often referred as mesh network.

One of the problems to be solved for such a multi-hop wireless infrastructure is the routing of traffic between terminals and base stations connected to the wired infrastructure. Compared to the routing problem in ad hoc networks, the problem is simplified, since nodes are stationary, and most traffic flows either begin or end in a limited set of nodes, i.e., those connected to the fixed infrastructure. On the other hand, since a significant amount of traffic is aggregated, the optimality of routing in terms of demand on the radio spectrum is much more important. The paths used should be such that the throughput of the wireless infrastructure is maximized, given a certain available spectrum and base station receiver sensitivity. We do this by introducing a new cost metric, based on the interference generated to transfer data over a specific link, and by using Dijkstra's shortest path algorithm to determine routes. Our analysis reveals that this cross-layer optimization leads to significantly increased data rates in the same radio spectrum, compared to traditional routing algorithms.

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* Corresponding author. Tel.: +31 53 489 5693; fax: +31 53 489 4524.
E-mail addresses: geert.heijenk@utwente.nl (G. Heijenk), fei.liu@utwente.nl (F. Liu).

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Routing in wired networks is relatively well understood. In wireless access networks, such as 3G cellular networks and wireless LANs, the wireless part of the network is confined to the last hop. As a result, routing comes down to finding the closest access point and routing in the wired part of the network, although the problem is complicated by the dynamics caused by end node mobility. The routing problem in multi-hop wireless networks is much more a research challenge. Considerable research has been done in the area of protocols for routing in ad hoc networks, which is a very difficult problem [1]. This has lead to proposals that do not scale very well, and are not optimal in terms of spectrum utilization. Nodes in multi-hop wireless networks do not have to be always mobile. The above-mentioned scenario of a multi-hop wireless infrastructure is such a network with stationary wireless nodes.

This paper is organized as follows. Section 2 sketches in which context, and under what assumptions, our routing algorithm has been developed. Section 3 describes existing interference-based routing algorithms, and describes the proposed balanced interference routing algorithm (BIRA). The performance of BIRA is modeled and evaluated in Section 4. In Section 5, conclusions and future work are given. BIRA has been introduced earlier in [2]. This paper provides a more extensive analysis of the proposed algorithm. More details of the modeling are given in [3].

2. Context and assumptions

Our work focuses on the routing problem in a multi-hop wireless infrastructure, such as the one depicted in Fig. 1. The network considered consists of a large number of stationary relaying base stations, and a limited number of special base stations with connection to the fixed network. Each base station serves a number of mobile terminals, with a total offered load of d Mbits per second per base station. All of the offered traffic in a base station is destined for the fixed network. The traffic is relayed via zero or more other base stations to the fixed network. The same amount of carried traffic is to be transported from the fixed network to each of the base stations, i.e., d Mbits per second per base station.

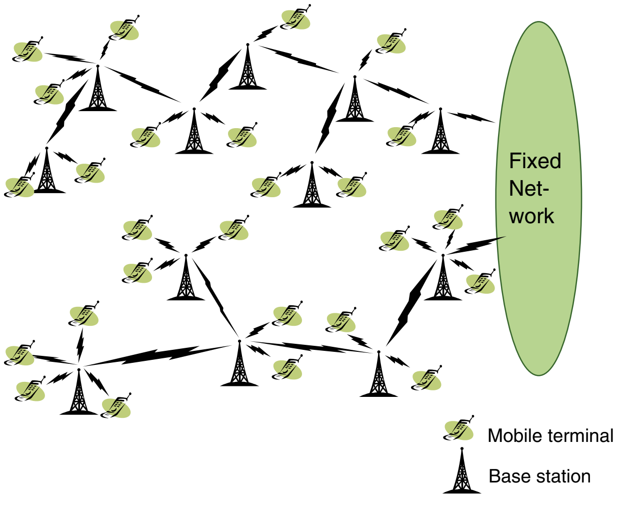

Fig. 1. Multi-hop wireless infrastructure.

It is assumed that the base stations use CDMA as the access technique for their interconnection network. Perfect power control is assumed for this CDMA network, so that all transmitters use just the transmission power level that is needed to let the receiver decode the signal with the proper quality. That is, the received signal meets the signal over interference ratio requirements (SIR_{target}) of the receiver hardware. It is also assumed that all transmitters have the same maximum transmission power, so that, as interference levels increase, some transmitters are not able to increase their transmission power any further, which will cause the link between this transmitter–receiver pair to fail.

With respect to the propagation environment, we assume that the signal is only deteriorated by path loss. So the signal strength is assumed to only depend on the transmission power and the distance. It is assumed that the signal strength is decreasing with the distance to the power α, with α between 3 and 4, as is known from experience in many CDMA networks [4]. It is finally assumed that the signal strength decay between each pair of base stations is known. This information can be obtained from feedback on previous transmissions (e.g., from power control information). Alternatively, this information can be derived from the distance between base stations. This can also be learned from previous transmissions (e.g., derived from the timing advance) or derived from positioning information (e.g., using a GPS receiver). In the remainder of this paper, it is assumed that the distance between base stations is known, although this does not preclude the former scenario.

3. Interference-based routing

3.1. Existing routing algorithms

In recent years, there has been a lot of work on wireless mesh networks and multi-hop routing algorithms (e.g., 802.11s [5], TORA [6] and AODV [7]). Here, we are mostly interested in related interference-based routing algorithms. Two such algorithms are least interference routing (LIR) [8] and minimum interference routing algorithm (MIRA) [9]. In the latter algorithm, the term "interference" does not really refer to the meaning of interference received from the physical layer. Indeed, it focuses more on a better distribution of the network "load". However, in wireless networks the interference at the physical layer is one of the main issues to be solved. The first algorithm will be discussed in some more detail below.

LIR computes a minimum-cost route metric. The cost of the links here takes the possible interference into account. The interference metric is created in each node. The interference generated by a node is considered to be the number of neighbours that can receive a transmission from that node. Therefore, the interference information can be calculated locally. Based on this interference metric, routes are calculated using Dijkstra's algorithm. LIR helps to lower the probability of interference to neighbours efficiently. Since the paths are calculated only based on the number of neighbours who can overhear a transmission, LIR is a simple algorithm to implement.

In CDMA type of networks, it is not sufficient that the interference a transmitter generated only takes the number of neighbours who can listen to a transmission into account. A transmitter can send signals to several receivers at the same time by using different codes with certain transmission power. In this case, the interference a node receives is also related to the distance to the transmitter. With the same transmission power, the closer nodes receive higher interference. Besides, the link cost is not only based on the interference. There are other factors influencing the computing of the routes, such as the number of hops, fixed link cost, error rate, reliability, etc. Based on the reasons mentioned above, we are going to propose a better interference-based routing algorithm for CDMA type of networks.

3.2. The need for interference-based routing

It is known that in CDMA systems, decrease of interference translates directly into increase of capacity. If interference at the receiver is decreased, less energy per bit is needed to correctly decode the signal. As a result, the transmitter can transmit with less power, which translates in again decreased interference at the other receivers, or transmission at a higher bit rate. This is why power control is so important in CDMA systems, as it reduces the transmission power of transmitters to adjust the level needed to correctly decode the signal at the receiver.

When faced with the problem introduced in Section 2, one straightforward solution might seem to be to let all base stations transmit their signal to the one connected to the fixed network in a single hop. However, since potentially large distances have to be bridged, this leads to high transmission powers, which in turn interfere with other transmissions. Breaking up a large transmission link into stages leads to a transmission power (measured at the transmitters) that increases linearly with distance. For transmission in a single stage, it is a known phenomena that the signal strength decays with the distance to the power α, with α between 3 and 4. This suggests that it is beneficial to break up a transmission path and to use multi-hop transmissions instead.

As we see the impact of interference on network capacity, it seems also important to decrease the interference caused by transmissions as much as possible. In a mesh type of network, this can be done by using transmitting nodes that are geographically far away from other (receiving) nodes in the network, because of the decay of the signal strength with distance. So, by taking the interference level caused by transmission over a certain link into account, we can balance and minimize the transmission power in the entire network and increase the network capacity. This will result in a higher offered load per base station, supported by the wireless multi-hop infrastructure.

3.3. Algorithm definition

Balanced interference routing algorithm (BIRA) is an algorithm which we propose for interconnection of base stations to the wired infrastructure via multiple wireless hops. It takes the interference a transmitter generates to the other nodes and a fixed transmission cost of each link into account. The idea of this algorithm is to try to generate a new cost function for all the links and compute the routing according to this cost based on the Dijkstra algorithm. The resulting routes constitute a spanning tree to/from the gateway node. To simplify the problem, in this paper, we assume only a single gateway node connected to the external infrastructure for each network area.

Let C_{ij} denote the cost for the link between i and j. We define the link cost:

$$C_{ij} = \beta A_{ij} + (1 - \beta) IL_{ij}. \tag{1}$$

This link cost function constitutes of two parts, weighted by the weight factor β. A_{ij} stands for a fixed cost for the link between i and j. Further, IL_{ij} is the interference level of the link between node i and j, generated to the other nodes in the network.

Let us first look at the case where the traffic flows are unidirectional, i.e., traffic is flowing on the links between nodes in a single direction, from the relaying base stations to the gateway node. For determining the interference level, let us consider an arbitrary node r (see Fig. 2a). It will receive interference from the transmission from i to j, when i is sending packets to j, with a power of

$$I_{ir,j} = \frac{P_{ij}}{D_{ir}^{\alpha}}, \tag{2}$$

where $I_{ir,j}$ denotes the interference r receives from the signal i sent to j, and D_{ij} represents the distance between station i and j. The transmission power P_{ij} of the transmission from node i to node j declines with the distance between i and receiver with power of α, where α is again the propagation path loss decay exponent. For a certain reference received power P_{ref} at the receiver j, the transmission power of node i for its transmission to j should be

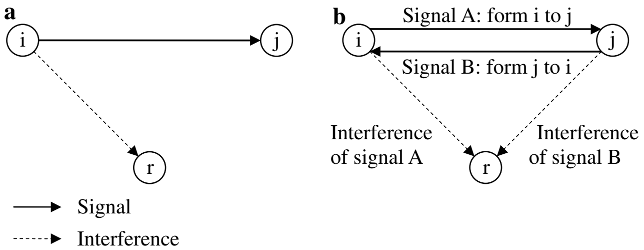

Fig. 2. Interference of i–j transmission to r for (a) unidirectional and (b) bidirectional flows.

$$P_{ij} = D_{ij}^{\alpha} P_{\text{ref}}. \tag{3}$$

So the interference at node r will be

$$I_{ir,j} = \frac{D_{ij}^{\alpha}}{D_{ir}^{\alpha}} P_{\text{ref}}. \tag{4}$$

The related interference level, relative to the same reference received power P_{ref} at node r, will be

$$IL_{ir,j} = \frac{I_{ir,j}}{P_{\text{ref}}} = \left(\frac{D_{ij}}{D_{ir}}\right)^{\alpha}. \tag{5}$$

In order to obtain the overall interference level of the link from node i to node j, we sum over all potentially interfered nodes r:

$$IL_{ij} = \sum_{r \neq i, r \neq j} \left(\frac{D_{ij}}{D_{ir}}\right)^{\alpha}. \tag{6}$$

Let us now consider the case where traffic flows are bidirectional. Traffic is assumed to flow over the links between nodes in both directions. To obtain the interference level, we add the interference generated by the transmission from i to j and the interference generated by the transmission from j to i, and sum over all potentially interfered nodes r (see Fig. 2b):

$$IL_{ij} = \sum_{r \neq i, r \neq j} \left(\left(\frac{D_{ij}}{D_{ir}}\right)^{\alpha} + \left(\frac{D_{ji}}{D_{jr}}\right)^{\alpha}\right). \tag{7}$$

Using the link costs defined above as input to the Dijkstra algorithm results in routes that tend to cause least interference to other node transmissions. Because power control used in CDMA systems decreases transmission power so that the required signal to interference ratio SIR_{target} is just met at the receiver, decrease of interference results in decrease of required transmission power per bit. As a result, the use of BIRA defined above will translate into increased capacity of the network.

From our experiments, we have observed that using just the interference level as a link cost metric will in some situation cause very long chains of nodes to be constructed as routes. This is not necessarily good, as in such a chain, each base station has to transmit both its own traffic load and the load received from the previous base station to the next base station, and the traffic flows can take a large "detour". In Section 4.3, we show that introducing a fixed link cost weighted by β avoids this problem and increases the network capacity.

Typically, a node cannot transmit and receive at the same time in the same frequency band, as the interference generated by a node's own transmission would be too strong for the node to correctly receive the incoming signal. Therefore, we propose to divide the transmission capacity in two (either in frequency or in time), where a specific node always uses one frequency (or time slot) for transmission, and the other for reception. For that purpose, all nodes are divided into two groups, based on the distance (in number of hops) to the gateway node. During the transmission of the nodes with even number of nodes to the gateway node, the nodes with odd number of nodes to the gateway node will receive and vice versa. Note that this mechanism of dividing the transmission capacity relies on the use of static routing. It is not a feasible solution for networks with dynamic routing.

The main algorithm run by all nodes will thus be as follows:

i. Determine link costs using Eq. (1).
ii. Run Dijkstra algorithm to find spanning tree from/to gateway node.
iii. Determine transmission frequency/time slot, based on number of hops to gateway node (even/odd).

4. Performance modeling

In order to evaluate the performance of BIRA, we have developed a model of a multi-hop wireless infrastructure. This model is presented in Section 4.1. Using this model, we analyse the performance of BIRA, first for some basic network topologies, in Sections 4.2 and 4.3, and then for large number of randomly generated network topologies in Section 4.4. Analyses are performed both for the case of unidirectional flows and for bidirectional flows. In the analysis, we study the impact of our tuning parameter β, and compare BIRA with three other routing algorithms. These are the least interference routing (LIR) algorithm, described in Section 3.1, and two rather straightforward algorithms: minimum distance routing (MDR) and minimum hops routing (MHR). MDR uses the geographic distance between two nodes as link cost, whereas MHR gives each link an identical link cost. Note that MHR is equivalent to BIRA with $\beta = 1$. After using the Dijkstra algorithm to calculate least cost paths, MDR will give routes with minimum geographic distance, whereas MHR will give routes with a minimum number of hops.

For the BIRA algorithm, throughout this performance evaluation, we assume that the fixed link cost equals 1 ($A = 1$), and the propagation path loss decay exponent equals 3 ($\alpha = 3$). Furthermore, for all four algorithms, a maximum transmission range is assumed, i.e., links between nodes only exist when the distance between the nodes is less than the transmission range.

4.1. Model

The model describes a set of n nodes i ($1 \leqslant i \leqslant n$), where node n represents a gateway base station, connected to the fixed network, and all the other nodes represent stationary relaying base stations. We assume that each of the nodes inserts an amount of traffic into the network, destined to the gateway node n with a data rate of d Mbits/s. Further, for the analysis with bidirectional flows, the gateway node inserts for each other node in the network a traffic flow with a date rate of d Mbits/s into the network. The resulting transmission bit rate of a node i to a specific other node

j (b_{ij}) is a multiple of d Mbits/s, depending on the number of flows that are aggregated to (and from) the gateway node in that specific node. We implemented the aforementioned routing algorithms to find the routes used for the traffic flows and the transmission bit rates of each of the nodes.

We assume that the inserted traffic is transferred wirelessly between the nodes, using CDMA technology. For determining the transmission power P_{ij} required for the transmission from node i to node j, we use a formula derived from [10]:

$$P_{ij} = SIR_{\text{target}} \times \frac{\mu_i b_{ij}}{w} \times D_{ij}^{\alpha} \times \left(PN + \sum_{r \neq i} \frac{P_r \times CI_{rj}}{D_{ij}^{\alpha}} \right). \tag{8}$$

Here, μ_i is the activity level of node i and w is the chip rate used in the system. The resulting $(\mu_i b_{ij})/w$ is the reciprocal of the processing gain of the transmission. SIR_{target} is the required signal to interference ratio at the receiver, whereas PN is the background noise. In all the experiments of this paper, we assume that μ_i is 1, w is 3.84 Mchips/s, SIR_{target} is the linear equivalent of 5 dB and PN is calculated assuming a background noise of −174 dBm/Hz with 5 MHz bandwidth. The last term in the equation denotes the received interference at node j. CI_{rj} is 1 if node r is transmitting in the same frequency/time slot where node j is receiving, otherwise it is 0. Finally, P_i is the sum of the transmission powers of all transmission done by node i, i.e.

$$P_i = \sum_j P_{ij}. \tag{9}$$

Note that in case of unidirectional flows, each sender i will be transmitting to only one receiver j. Further, note that these equations assume the propagation channel only to exhibit path loss, perfect power control and complete orthogonality of multiple transmissions by the same node. By solving this system of equations iteratively, we can obtain the transmission power for each node. We ran a fixed number (10,000) of iterations, after which the change of transmission powers between subsequent iterations was negligible. Further, we varied the offered data rate per node d, to find the highest value for d, for which the transmission power of each node is below a predefined maximum value. Thus, we compared different routing algorithms with respect to the offered data per node a network can support. The model has been implemented in Matlab 6.5.

4.2. Basic analysis

Based on the model we introduced above, we start the comparison using a basic topology. Suppose in a $1000 \times 1000\,\text{m}^2$ network area, 10 base stations are distributed evenly in a straight line with the same space 100 m between neighbours. Station $\text{A}, \text{B}, \text{C}, \ldots, \text{H}$, and I are stationary relaying base stations, while J is connected to the fixed infrastructure by a wired connection. All the packets are sent to or received from (in the case of bidirectional flows) the fixed network via Station J. In this network, we can evaluate the potential gain of transmitting flows in multiple hops, instead of a single hop. If we apply MHR without communication range to compute the routes, all nodes will take a single hop to the destination. Intuitively, this will generate the most interference to the network. In this sense, MHR is not a suitable algorithm for the network. We are going to compare MHR with BIRA by observing the maximum data rate with different communication range. A larger maximum data rate from BIRA than from MHR is expected.

4.2.1. Methodology

In MHR, the cost of all the links is same. This implies that always the direct links are used, if the link is available. Through the model above, we can obtain the maximum data rate d in each node. We will compare the value of d for different algorithms, and see which algorithm can obtain the highest data rate/capacity.

4.2.2. Results

Fig. 3 shows two different routes obtained by MHR and BIRA (with weight parameter $\beta = 0.5$) with unlimited communication range. Fig. 3a shows that with MHR, all the relaying nodes reach the destination (J) within the least number of hops (a single hop in here). However, with BIRA, nodes are trying to reach the closest node in order to minimize the interference as show in Fig. 3b. Meanwhile, the fixed link cost A also tries to balance the length of branches, and avoid the long branches as we mentioned in Section 3.3, so that the first node chooses the path via the third node, instead of the second one.

Because the transmission power increases with the distance to the power of 3, the nodes in Fig. 3a need more transmission power to transmit the signals, which implies more interference in the network. Intuitively, the routes in Fig. 3b can decrease the interference and obtain larger data rate. The modeling results proved our assumption.

Table 1 shows the maximum data rates the network we describe can obtain by using algorithm MHR and BIRA with different communication range. $\text{D}_{\text{MHR-u}}$ and $\text{D}_{\text{BIRA-u}}$ represent the maximum data rate MHR and BIRA can obtain, respectively, in the unidirectional network; while $\text{D}_{\text{MHR-b}}$ and $\text{D}_{\text{BIRA-b}}$ refer to the results in the bidirectional network. It can be observed that bridging a distance in multiple hops really leads to an increased maximum data rate. MHR can be forced to do so, by limiting the communication range, whereas BIRA automatically chooses this optimal routing. It must be noted that this is an extreme case, in which the rationale behind the BIRA algorithm is exploited very well.

4.3. Rationale for adding fixed link cost

In Section 3.3, we have introduced a fixed link cost A_{ij}, as part of the cost metric for routing. The rationale for this will be illustrated in the next experiment. We have modeled

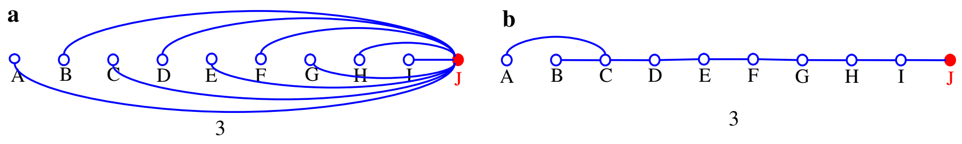

Fig. 3. Routes for MHR (a) and BIRA (b) with unlimited communication range.

Table 1
Maximum data rates for different communication range

Communication range (m)	100	200	400	600	800
$D_{MHR\text{-}u}$ (Mbit/s)	0.494	0.158	0.148	0.165	0.151
$D_{BIRA\text{-}u}$ (Mbit/s)	0.494	0.499	0.499	0.499	0.499
$D_{MHR\text{-}b}$ (Mbit/s)	0.105	0.027	0.008	0.005	0.002
$D_{BIRA\text{-}b}$ (Mbit/s)	0.105	0.105	0.105	0.105	0.105

a network with 30 nodes randomly distributed in an area of 1000 m × 1000 m, where the last generated node is the gateway node connected to the fixed network. We also assume that all the nodes have 600 m communication range. For the obtained topologies, we have compared a version BIRA, using only the interference level as a cost metric (i.e., $\beta = 0$) with a version adding a fixed link cost ($\beta = 0.5$). For some of the topologies generated, we found that BIRA with $\beta = 0$, using only the interference level as a metric, has poor performance. One of these topologies is discussed below. The experiments are using unidirectional flows.

4.3.1. Results

Fig. 4 shows the routes obtained for a certain topology, for $\beta = 0$ (Fig. 4a) and for $\beta = 0.5$ (Fig. 4b). In case $\beta = 0$, since the routing algorithm only considers the interference generated in the network, the routing algorithm always tries to find a nearby intermediate node to save transmission power in order to minimize the interference. So there are only three main branches to reach the destination, and each of them is very long. In such a chain, each base station has to transmit both its own traffic load and the load received from the previous base station to the next base station, and the traffic flows can take a large "detour". When a branch is long and has a lot of leafs, the last link is overloaded and the chip rate also limits the data rate. Compared with the routes in Fig. 4a, the routes shown in Fig. 4b are more balanced and well distributed. There are six main branches in the routes. Even the subbranch of the main branch is better balanced. In order to obtain these more appropriate routes, we have added a fixed link cost A_{ij}, to the cost metric (by choosing $\beta = 0.5$), so that the routing algorithm does not only minimize the interference, but also the number of hops for each flow.

The maximum achievable data rates per node for this specific topology also illustrate the difference between the two approaches. The data rate obtained if BIRA does not use a fixed link cost ($\beta = 0$) *is* 0.02375 Mbit/s, whereas the data rate obtained if BIRA uses both a fixed cost and the interference level ($\beta = 0.5$) is 0.050 Mbit/s.

4.4. Extensive analysis

In order to analyse a more realistic situation, in this subsection, we modeled a network with 30 nodes randomly distributed in an area of 1000 m × 1000 m, where the last generated node is the gateway node connected to the fixed network. Moreover, we assume that all the nodes have

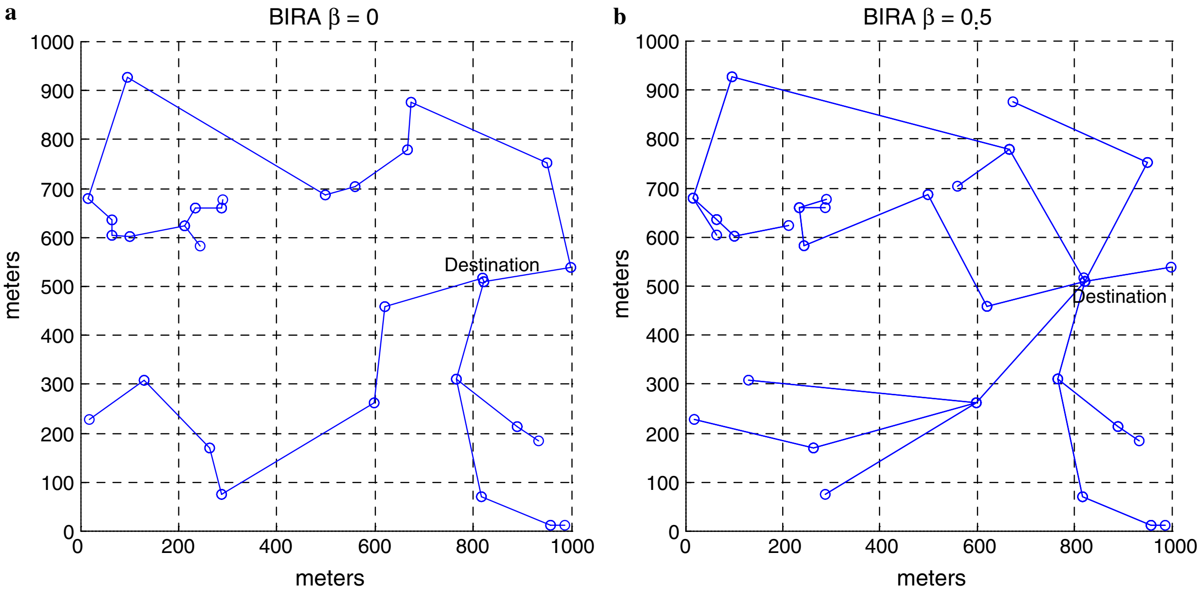

Fig. 4. Routes with (b) and without (a) fixed link cost.

600 m communication range. We will compare BIRA with different values of the weight parameter β to optimize the value of β. Furthermore, we will compare BIRA with several other routing algorithms, i.e., MDR, MHR and LIR.

4.4.1. Methodology

In order to compare these algorithms, we define

$$\delta = \frac{d_1 - d_2}{d_2} = \frac{d_1}{d_2} - 1, \tag{10}$$

where d_1 and d_2 denote the maximum achievable data rates for two different routing algorithms. When δ is equal to 0, $d_1 = d_2$, which is one of the important features of δ; when $\delta < 0$, $d_1 < d_2$; when $\delta > 0$, $d_1 > d_2$.

We generated several topologies. For each topology, we obtained a δ for a specific pair of routing algorithms. We further define the function

$$f(\delta = i) = \frac{\text{the number of } \delta, \text{ where } \delta \leqslant i}{\text{the total number of } \delta}. \tag{11}$$

Especially, $f(0)$ represents the fraction of cases where d_1 is worse than or equal to d_2. We also define $f(\uparrow 0)$, where $\uparrow 0$ represents an infinitesimal small value smaller than 0, which denotes the fraction of cases where d_1 is worse than d_2.

A $100(1 - \gamma)$ % confidence interval for the population mean is [11]

$$\left(\bar{\delta} - z_{1-\gamma/2}\frac{s}{\sqrt{n}}, \bar{\delta} + z_{1-\gamma/2}\frac{s}{\sqrt{n}}\right), \tag{12}$$

where $\bar{\delta}$ is the sample mean, s is the sample standard deviation, n is the sample size and $z_{1-\gamma/2}$ is the $(1 - \gamma/2)$-quantile of a unit normal variety. For a 90% confidence interval, the normal distribution quantile $z_{1-\gamma/2} = 1.645$. The confidence interval indicates the interval for the real mean with a certain percentage confidence. We are going to use this method to achieve the confidence interval for the real mean of δ.

4.4.2. Results

Two experiments are done to evaluate the performance of BIRA. The first experiment compares BIRA with different values of β in order to obtain the optimal value. We perform this optimization only for the case of bidirectional flows. With this optimal value, BIRA is compared with MHR, MDR and LIR in the second experiment.

In Experiment 1, we generate 100 topologies to compare BIRA with $\beta = \beta_1 = 0.4$ and $\beta = \beta_2 = 0$, 0.2, 0.5, 0.6, 0.8 and 1, respectively, so that d_1 stands for the data rate of $\beta = 0.4$, while d_2 represents the data rates of the others (see Table 2). We can observe that with 90% confidence the BIRA with $\beta = 0.4$ can achieve higher data rate in general than β equal to 0, 0.8 and 1. However, $\beta = 0.4$ has a similar but slightly better performance than $\beta = 0.2$, 0.5, or 0.6 based on that the mean value of δ is larger than 0 for those points, and $f(\uparrow 0)$ is smaller than 0.5. By comparing the value of $f(0)$ and 90% confidence interval of δ, we conclude that the optimal value of β lies between 0.2 and 0.6, whereas $\beta = 0.4$ seems to be a good choice.

Table 2
Comparison results of 100 samples for bidirectional network

β_2	Mean of δ	$f(0)$	$f(\uparrow 0)$	90% Confidence interval for mean of δ
0	0.076	0.330	0.300	(0.039, 0.112)
0.2	0.017	0.490	0.390	(−0.006, 0.039)
0.5	0.021	0.510	0.360	(−0.003, 0.045)
0.6	0.026	0.520	0.460	(−0.010, 0.061)
0.8	0.208	0.240	0.220	(0.101, 0.315)
1	1.793	0.350	0.350	(0.870, 2.717)

Table 3
Comparison results of 100 samples for unidirectional network

Algorithm	Mean of δ	$f(0)$	$f(\uparrow 0)$	90% Confidence interval for mean of δ
BIRA vs. MDR	0.2029	0.070	0.070	(0.177, 0.229)
BIRA vs. LIR	0.9854	0.410	0.400	(0.331, 1.639)
BIRA vs. MHR	0.1842	0.140	0.140	(0.116, 0.253)

We can also see that the case where $\beta = 0$, which implies a cost function only considering interference, does not perform as good as the case $\beta = 0.4$. This confirms our rationale in Section 4.3 that only considering interference level will sometimes result in extreme long routes to the destination which restrict the data rate of the network. Taking fixed link cost into account can help to balance the length of the routes and to obtain the higher data rates.

In Experiment 2, we take $\beta = 0.4$ and compare BIRA with MHR, MDR and LIR by analyzing the results of 100 topologies in both networks with unidirectional (uplink) flows and networks with bidirectional flows. We define the data rate of BIRA as d_1 and the others as d_2. For both cases (uni- and bidirectional flows), we give a table with the main results of the comparisons and a figure in which the function f is plotted for the three comparisons.

The results for unidirectional flows are shown in Table 3 and Fig. 5. Comparing BIRA with MDR, we see that in only 7% of the cases MDR obtained a higher data rate than BIRA. In all other cases, BIRA achieved a higher data rate. On average, BIRA obtains 1.2 times the data rate of MDR. BIRA also performs much better than MHR. We found that the mean of δ is 0.18, which indicates that on average the data rate obtained by BIRA is 1.18 times the one obtained by MHR. Among 100 topologies, there are 86% of the cases where BIRA had a better performance than MHR. In general, we found that LIR has slightly better results than MDR and MHR. $f(0)$ is 0.41, so that in 59% of the topologies BIRA performed better than LIR. However, since the mean of δ is 0.99, the data rate obtained by BIRA is on average 2 times the one obtained by LIR. For some topologies, LIR obtained very unfavourable results.

The results of the comparison of BIRA with the alternative routing algorithms in the case of networks with bidirectional flows are given in Table 4 and Fig. 6. For bidirectional flows, when comparing BIRA with MDR,

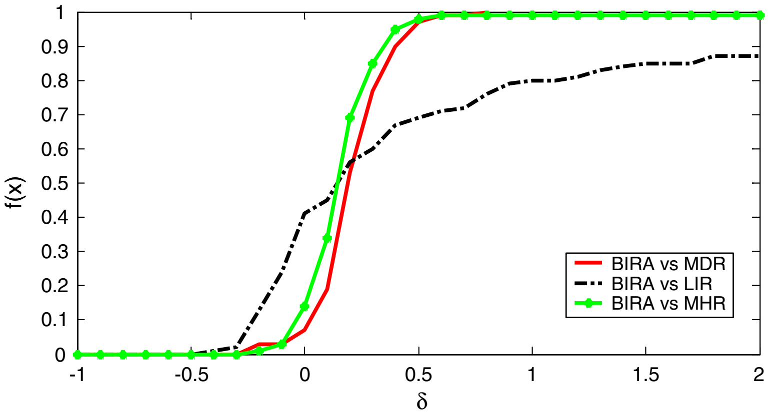

Fig. 5. Comparison of BIRA with alternative routing algorithms for unidirectional flows.

Table 4
Comparison results of 100 samples for bidirectional network

Algorithm	Mean of δ	$f(0)$	$f(\uparrow 0)$	90% Confidence interval for mean of δ
BIRA vs. MDR	1.5354	0.130	0.130	(1.041, 2.030)
BIRA vs. LIR	1.4210	0.220	0.200	(0.584, 2.258)
BIRA vs. MHR	1.7934	0.350	0.350	(0.870, 2.717)

we found that the date rate obtained with BIRA is on average 2.5 times the data rate obtained with MDR, and in 87% of the topologies, BIRA had better performance. When comparing BIRA with MHR, BIRA obtains on average 2.8 times the data rate of MHR, and in 65% of the topologies BIRA achieves better performance than MHR. Finally, BIRA obtains on average 2.4 times the data rate of LIR, and in 78% of the topologies BIRA obtains higher data rates than LIR.

5. Conclusions and future work

A new routing algorithm for multi-hop wireless infrastructures, the balanced interference routing algorithm (BIRA), was proposed. BIRA is promising for the interconnection of high density base stations, where some of the base stations do not have a direct connection to the fixed network. Such a base station will send/receive packets to the wired infrastructures via multiple hops. BIRA is based on the Dijkstra algorithm, where the link cost is a weighted combination of fixed link cost and interference level. Modeling and performance analysis shows that using a combination of fixed link cost and interference level yields better performance than using one of the two as a cost function. More specifically, using a weight factor, β, of 0.4 is definitely better than using β below 0.2, or above 0.6, whereas, it is probably better than other values within this interval. BIRA with the value of $\beta = 0.4$ outperforms the MHR, MHR and LIR algorithm in terms of obtained data rates for a given available spectrum. This applies both to the case where data are flowing in two directions to and from the fixed network, and to the case where data are only flowing in the direction of the fixed network. Compared to a routing algorithm that minimizes hop count (MHR), BIRA obtains better routes for unidirectional flows in 86 out of 100 randomly generated topologies, resulting in a maximum achievable data rate that is on average 18% higher. For bidirectional flows, BIRA outperforms MHR in 65 out of 100 topologies, resulting in an average performance gain of 180%. It can be concluded that BIRA really

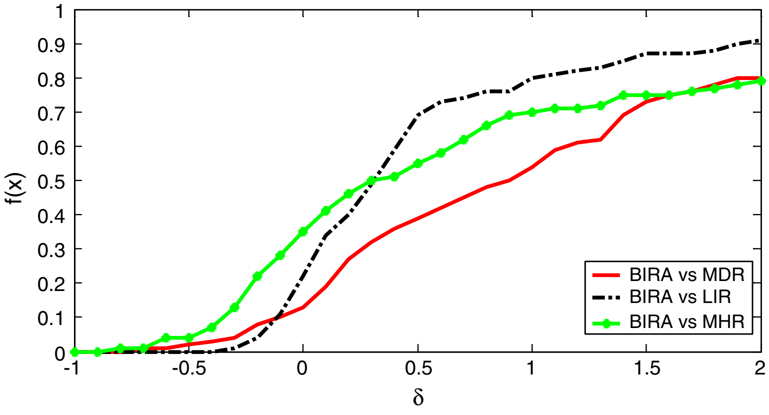

Fig. 6. Comparison of BIRA with alternative routing algorithms for bidirectional flows.

helps to reduce the interference in the network and to achieve higher throughput.

Further work includes the extension of BIRA to situations where the node locations are unknown, so that interference levels have to be derived from physical layer procedures, e.g., from power control information. Also, the extension of BIRA, to allow for rerouting to cope with link or node unavailability, needs to be investigated. The ideas of BIRA have to be incorporated in a routing protocol, suitable for wireless environments. Finally, analysis of topologies with multiple gateway nodes has to be performed. The application of interference-based routing to multi-hop wireless systems with random access techniques such as the one used in IEEE 802.11 Wireless LAN is also a promising field of research.

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Geert Heijenk (1965) received his M.Sc. in Computer Science from University of Twente, the Netherlands, in 1988. He worked as a research staff member at the same university and received his Ph.D in Telecommunications in 1995. He has also held a part-time position as researcher at KPN research, the Netherlands, from 1989 until 1991. From 1995 until 2003, he was with Ericsson EuroLab Netherlands, first as a senior strategic engineer, and from 1999 as a research department manager. From 1998 until 2003 he was also a part-time senior researcher at the University of Twente. Currently, he is a full-time associate professor at the same university. His research interests include mobile and wireless networks, resource management, and quality of service.

Fei Liu (1980) is a Ph.D. candidate at the University of Twente, the Netherlands. She received her B.Sc. degree in Computer Science from Jiangsu Institute of Petrochemical Technology, China, in 2002, and her M.Sc. degree in Telematics from University of Twente, the Netherlands, in 2004. Her research interests include mobile and wireless networks, particularly networking and mobility support.