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A new approach to design of weather disruption-tolerant wireless mesh networks

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Abstract Wireless Mesh Networks, offering transmission rates of 1–10 Gb/s per a millimeter-wave link (utilizing the 71–86 GHz band) seem to be a promising alternative to fiber optic backbone metropolitan area networks because of significantly lower costs of deployment and maintenance. However, despite providing high transmission rates in good weather conditions, high-frequency wireless links are very susceptible to weather disruptions. In particular, heavy rain storms may lead to remarkable signal attenuation. In this paper, we introduce a new transmission technique for wireless mesh networks to mitigate the negative effects of link quality degradation due to rain storms. In particular, our method is the first one to use information on forecasted attenuation of links based on radar measurements to perform in advance the periodic updates of a network topology. Our approach is easily implementable in practice, since functionality of dynamic antenna alignment is currently offered by a number of equipment vendors. Other contributions of the paper include presentation of the ILP model of weather-resistant links formation problem followed by analysis of its computational complexity. Results of simulations, performed for three real scenarios of rain storms, show that our approach is very efficient in reducing the level of signal attenuation.

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1 Introduction

Owing to utilization of the 71–86 GHz band, Wireless Mesh Networks (WMNs) formed by stationary routers forwarding data from mobile (or stationary) users, are able to offer high transmission rates (i.e., 1–10 Gb/s) per a millimeter-wave link [1–5]. Therefore, they may soon become a proper alternative to wired local, metropolitan, or even wide-area networks. It seems that the idea of replacing the fiber optic technology by WMN solutions, raised by people from both academia and industry, is well justified for economical, as well as practical reasons. It is especially likely for 3G (4G) operators who do not have their own fiber infrastructure. For them, the only alternate solutions would be either to try to lease capacity from other network providers, or to deploy their own fiber network (which, however, may be very expensive in rural areas).

One of the most important issues in design of WMNs is related to reliability of high-frequency wireless communications, often encountering availability problems. For instance, millimeter-wave WMN links are very susceptible to weather disruptions (especially due to precipitation) [6]. As a result of heavy rain storms causing high signal attenuation, available link capacity may be seriously reduced. In the worst case, this may imply a complete failure of communication links bringing about further instability problems of end-to-end paths (e.g., route flapping).

Network operators are convinced that for certain classes of service, offering the required level of transmission quality is not possible without applying the proper means of protection against disruptive events.

Transmission reliability can be improved by using *network survivability* mechanisms aimed at providing the continuous service in the presence of failures [7–9]. They were originally proposed for wired networks, and typically utilize the idea of *backup* (*alternate*) *paths* [10] forwarding the traffic after failures of links/nodes affecting the respective *primary paths* of transmission. In general, in order to provide protection against failures of links/nodes, every alternate path should be link-(node-)disjoint with the respective primary path [11,12].

Failures of links/nodes in wired networks are commonly considered as random. However, this is often not true for WMNs due to frequent *spatial correlation* of disruptive events. For instance, a group of wireless links located in the same area of a rain storm, may jointly encounter degradation of their effective capacity. As shown in [13,14], such *region disruptions* (i.e., events occurring in the area of a negative factor influence), are neither equally probable, nor statistically independent.

In this paper, we address the issue of survivable routing in wireless mesh networks. In particular, our main focus is on reducing the level of signal attenuation along WMN links during rain storms.

This paper includes four original contributions. The first one is the introduction of a method to decrease the level of signal attenuation as a result of rain storms by performing in advance the periodic updates of a network topology (i.e., wireless links) based on forecasts of heavy rain storms (using the functionality of a dynamic antenna alignment). This feature is offered by a number of equipment vendors, (see e.g., [15]), which makes our approach easily implementable.

Second contribution is the ILP model proposed to obtain the optimal configuration of WMN links with respect to the forecasted levels of signal attenuation, that also provides a proper selection of non-interfering channels for intersecting links. Another original result is the analysis of computational complexity of the problem followed by justification of a sub-optimal heuristic algorithm utilization. Final achievement is the evaluation of the proposed approach characteristics by means of simulations.

It is worth noting that protection of WMNs against weather-based link failures occurring in given regions has not gained much attention in the literature so far. In particular, to the best of our knowledge, there is currently no reliability approach available in the literature that is based on periodic updates of a network topology.

The rest of the paper is organized in the following way. Section 2 provides a detailed analysis of related works, while Sect. 3 presents our approach of periodic updates of a WMN topology utilizing radar echo rain measurements. Sections 4 and 5 include analysis of simulation results and conclusions, accordingly.

2 Related works

Papers on region failures available in the literature are dedicated mainly to wired networks [16–20] with special focus on optical WDM networks protection (e.g., [16,17,21,22]). Among few proposals concerning reliability of transmission in wireless networks, we can mention works related to routing issues addressing shared medium problems, or nodes mobility [23]. However, these approaches cannot be applied to WMNs in a straightforward manner due to remarkably different characteristics. Indeed, wireless mesh networks are commonly non-mobile, as well as, if equipped with highly directional antennas, do not encounter contention problems. We can even say that WMNs seem to share their major characteristics with wired networks (the only clear exception is related to link stability characteristics) [24].

Authors of papers related to WMN survivability commonly assume that the connectivity of a network topology is the main measure of its fault tolerance [25]. In particular, papers [26,27], and [28] present specific variants of connectivity measures, namely: average connectivity, distance connectivity, or path connectivity, accordingly. However, these proposals are not suitable to provide the qualitative measures (e.g., regarding the overall flow surviving a failure). This is because the respective metrics from [25–28] were proposed only to give the “yes/no” answer whether the topology of a network is k-connected, i.e., if transmission still remains possible after the multiple failure of k-1 network components.

Recent works on region failures typically consider circular disruption areas (see Fig. 1 and [29]) defined with respect to either network geometry, or topology. For example, in [30] region failures are modeled by means of circles of constant radius r. Another assumption of [30] is that probability p_i of node n failure (being a monotonously decreasing function of distance r_n of node n from the failure epicentre), is constant within each ith area between two consecutive concentric annuli (see Fig. 2). However, in case of weather disruptions addressed in this paper, such an assumption could lead to over-, or underestimation of the level of signal attenuation.

Besides, representing the regions of rain disruptions by circular areas is often misleading due to non-deterministic rain storm characteristics over time. It seems reasonable to utilize the weather forecast information (e.g., achieved from radar echo measurements) to predict the real (frequently non-circular) shapes of signal attenuation regions.

Based on such an idea, two algorithms have been proposed in [24], namely XL-OSPF and P-WARP, accordingly, to use rain predictions to modify in advance the link-state Open Shortest Path First (OSPF) routing. Both algorithms utilize formulas (1)–(2), originally introduced in [31], to define the signal attenuation level depending on the rain rate.

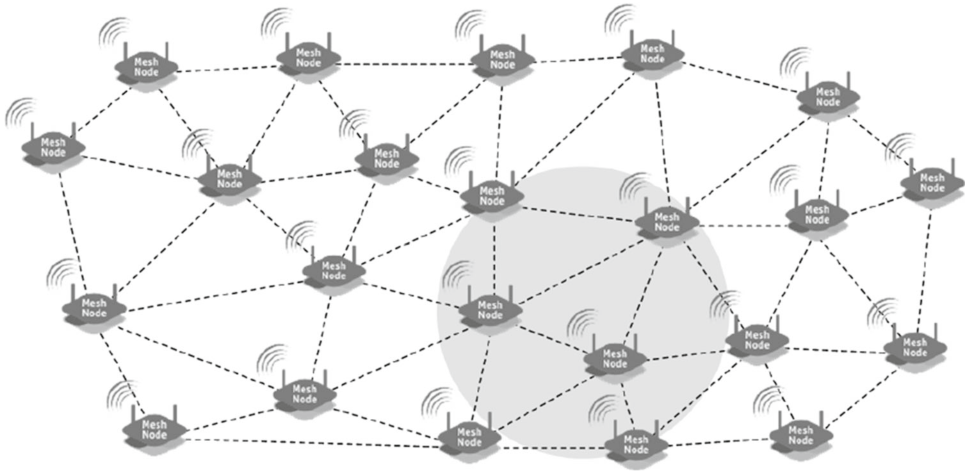


Fig. 1 Example circular region of disruptions

$$A(R_p, D) = \alpha R_p^{\beta}\left[\frac{e^{u\beta d}-1}{u\beta} - \frac{b^{\beta}e^{c\beta d}}{c\beta} + \frac{b^{\beta}e^{c\beta D}}{c\beta}\right]$$

$$d \le D \le 22.5\,\text{km} \tag{1}$$

$$A(R_p, D) = \alpha R_p^{\beta}\left[\frac{e^{u\beta d}-1}{u\beta}\right];\, 0 \le D \le d \tag{2}$$

where:

- A is the attenuation of signal in dB,
- D is the length of the section of the path (in km) over which the rain is encountered,
- R_p is the rate of rain in mm/h,
- α, β are the specific constants taken from [31],
- $u = \frac{ln\left(be^{cd}\right)}{d}$,
- $b = 2.3R_p^{-0.17}$,
- $c = 0.026 - 0.03lnR_p$,
- $d = 3.8 - 0.6lnR_p$.

In XL-OSPF, a special metric of link costs was introduced that is proportional to the observed bit error rate (BER) of the link. This is reasonable, since signal attenuation has a direct influence on BER (bit error rate), as well as on PER (packet error rate) values observed at higher network layers. This metric was next used to update the OSPF routing characteristics in a reactive manner. However, since in MAC layer there is no direct information on the actual BER exchanged between network nodes (BER can be only estimated based on signal-to-noise ratio (SNR) information), such an approach is not easy to deploy [24].

Unlike XL-OSPF, P-WARP algorithm estimates link costs based on weather-radar information used to predict the future conditions of links. These calculations can be performed at either one dedicated (core) node, or at a set of nodes capable of collecting the weather-related data. In each case, weather radar information has to be broadcast to all the network nodes, additionally increasing the routing algorithm complexity.

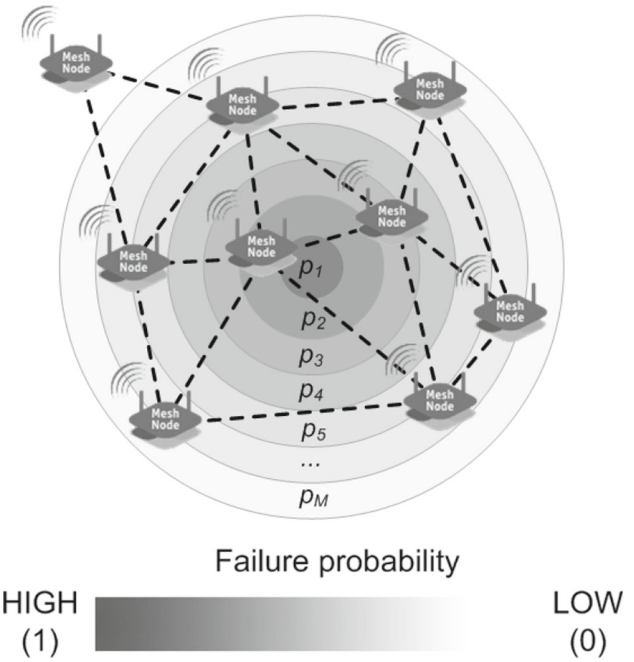


Fig. 2 Example circular area of region failures from [30]

Available methods of weather-resistant WMN routing seem to be focused mainly on updates of link cost metrics, and do not use other information (e.g., related to network characteristics). In particular, to the best of our knowledge, so far there has been no approach proposed in the literature to improve the performance of a WMN during rain storms that is based on automatic updates of a WMN network topology.

3 Proposed approach

In order to provide easy deployment, as well as not to increase the complexity of a routing algorithm itself, in our proposal we do not modify characteristics of the routing algorithm. Communication paths are thus established here based on conventional metric of link costs (e.g., based on the number of hops).

Our main idea is to improve the throughput of a wireless mesh network during rain storms by utilizing the periodic updates of a network topology. We propose to apply these updates by means of dynamic antenna alignment features offered by a number of equipment vendors. In particular, in our approach, periodic updates of a network topology depend on characteristics of real echo rain maps used to forecast the future conditions of links. In practice, this implies dynamic formation (or removal) of communication links, if low (or high) values of signal attenuation are expected for them, accordingly. As a result, the network is prepared at any time to changing weather conditions, which in turn may help to provide guarantees on 50 ms restoration time values, required for a number of services.

The structure of a wireless mesh network is modeled here by graph $\Gamma = (N, E, T, \varphi(t), \gamma(t))$, where:

- N denotes the set of network nodes. In this paper, we assume that unlike in mobile networks (e.g., in VANETs [32–35]), nodes are stationary here, i.e., their location does not change over time (which is a common scenario for WMNs),
- E is used to model the set of network links. Any connection between two neighboring nodes i and j is modeled by two directed egdes $e_h = (i, j)$ and $e_{h'} = (j, i)$, accordingly, and is assigned a given transmission channel from the set of Λ transmission channels,
- T is the lifetime of a network used to model the time-varying existence of wireless mesh links,
- $\varphi(t)$: E x $T \rightarrow \{0, 1\}$ is a function determining the existence of links at time $t \in T$,
- $\gamma(t)$: E x $T \rightarrow \mathbb{R}$ is a function determining costs a_h of links e_h based on signal attenuation ratios at time $t \in T$ as given in formulas (1)–(2).

It is worth noting that nodes mobility implying time-dependent node presence (which is out of scope of this paper) could be easily added to the considered scenario by incorporating the respective node existence function $\Upsilon(t)$: N x $T \rightarrow \{0, 1\}$.

We assume that alignment of antennas of all network nodes is determined by a dedicated core node having access to the following information:

- Set of active network nodes and their locations,
- Radar echo rain measurements received periodically,
- Demands to provide transmission between pairs of end nodes p and q.

The core node is responsible for executing the proposed algorithm. In Step 1, for each pair of adjacent (neighboring) nodes i and j—i.e., located in the nearest vicinity with respect to each other, the algorithm first calculates the estimated signal attenuation a_h at each potential edge $e_h = (i, j)$, using formulas (1)–(2).

Algorithm 1: Proposed methodology of periodic updates of alignment of WMN antennas

```
INPUT:
  – Set of network nodes $N$,
  – Coordinates $(x_i, y_i)$ of each node $i$,
  – Initial set of network links extended by possible links between
    each pair of neighboring nodes,
  – Aggregate demand volumes for each pair of nodes $p$ and $q$,
  – Information on current radar echo rain measurements,
  – Frequency of antenna alignment updates given by interval $c$

OUTPUT:
  – New alignment of antennas corresponding to the forecasted
    level of signal attenuation based on rain storm predictions.

Step 1. For each pair $i$ and $j$ of neighboring nodes, determine
        the forecasted signal attenuation $a_h$ of a link (represented
        by two edges $e_h$ in opposite directions) to be
        potentially installed between nodes $i$ and $j$.

Step 2. Determine a new configuration of links based on estimated
        values of signal attenuation $a_h$ from Step 1. For
        this purpose:
        (a) For each demand to provide transmission
            between nodes $p$ and $q$, find the cheapest transmission
            path in terms of costs $a_h$,
        (b) Make the decision to create wireless links only
            between nodes that forward the traffic (based on
            information after Step 2a).

Step 3. Based on results of Step 2, distribute the respective
        information among all network nodes to configure
        the alignment of WMN antennas.

Step 4. Wait for $c$ time units and next go to Step 1.
```

Step 2 is to determine a new configuration of links. For this purpose, values a_h are treated as link costs to obtain the set of the cheapest (in terms of signal attenuation) potential paths. In general, if in Step 2 a given link is not used by any path, it will not appear in the updated topology. At this point, it is worth noting the necessity to select transmission channels in a way to avoid interference of intersecting links.

New alignment of antennas is next determined in Step 3 after passing the respective antenna alignment information to all network nodes. As a result, certain WMN links will/will not be created for the forthcoming period of time (comprising c time units) owing to predicted low/high signal attenuation, accordingly. The next update of a network topology is expected after c units of time have elapsed (Step 4).

Metric a_h is used in our algorithm only to update the alignment of antennas. Between any two consecutive updates of a network topology, routing is done by means of a conventional protocol (e.g., OSPF) with all its characteristics unchanged. In particular, real transmission paths are determined based on a common hop count metric (instead of a_h values).

Details concerning the execution of Step 2 of our algorithm are included in Sects. 3.1 and 3.2 of this paper. In Sect. 3.1, we introduce the Integer Linear Programming (ILP) model to determine the optimal solution to the problem from Step 2, followed by analysis of its computational complexity (Sect. 3.2). As a criterion function, we use minimization of the aggregate signal attenuation over all transmission paths. In particular, the proof of *NP*-completeness of the considered problem, presented in Sect. 3.2, provides justification of using heuristics in simulations.

3.1 ILP model of weather-resistant links formation problem (WRLF)

ILP model presented in this section can be used at a given time t to find a new optimal configuration of links (Step 2 of Algorithm 1) in terms of minimizing the overall signal attenuation during rain storms. For this purpose, based on estimated values a_h of signal attenuation of links e_h, it determines the cheapest set of transmission paths (in terms of the aggregate value of signal attenuation over all transmission paths) with proper channel assignment to avoid mutual interference of intersecting links. It thus considers an instant network topology graph defined by the set of nodes and links available at time t.

Indices

$\Gamma(N,E)$	Directed network
N	Set of network nodes; $\|N\|$ is the number of network nodes
E	Set of directed edges used to model the network links; $\|E\|$ is the number of edges
D	Set of demands; $\|D\|$ is the number of demands
r	Demand index; $1 < r \leq \|N\| \cdot (\|N\|-1)$; $r = 1, 2, \ldots, \|D\|$
$p_r(q_r)$	Source (destination) node of rth demand
f_r	Capacity of rth demand
$1\ldots\Lambda_h$	Indices of transmission channels available at edge $e_h=(i,j)$; $\forall_h \Lambda_h = \Lambda$
c_h^t	Estimated total capacity of edge $e_h=(i,j)$ at time t
a_h^t	Estimated signal attenuation due to rain falls for edge e_h at time t

Variables

$x_{r,h}^l$	Takes value of 1, if lth channel of edge $e_h=(i,j)$ is allocated for a transmission path of rth demand; 0 otherwise

Objective

It is to find end-to-end paths for all aggregate demands minimizing the following linear cost:

$$\varphi(x,t)=\sum_{r=1}^{|D|}\sum_{l=1}^{\Lambda}\sum_{h=1}^{|E|} a_h^t \cdot x_{r,h}^l \qquad (3)$$

where: a_h^t is a cost of edge $e_h=(i,j)$ based on estimates of signal attenuation ratio at time t.

Constraints

(a) Flow conservation constraints for transmission paths:

$$\sum_{l=1}^{\Lambda}\sum_{\substack{h\in\{h:e_h\equiv(n,j)\in E\};\\ j=1,2,\ldots,|N|;\,j\neq n}} x_{r,h}^{l}-\sum_{l=1}^{\Lambda}\sum_{\substack{h\in\{h:e_h\equiv(i,n)\in E\};\\ i=1,2,\ldots,|N|;\,i\neq n}} x_{r,h}^{l} = \begin{cases}1 & if\ n=p_r\\ -1 & if\ n=q_r\\ 0 & otherwise\end{cases} \qquad (4)$$

where:

$e_h=(i,n)$ edge incident into node n
$e_h=(n,j)$ edge incident out of node n
$r=1,2,\ldots,|D|$
$n=1,2,\ldots,|N|$

(b) Finite channel capacity constraints for edges e_h at time t:

$$\sum_{l=1}^{\Lambda}\sum_{r=1}^{|D|} x_{r,h}^l \cdot f_r \leq c_h^t \qquad (5)$$

where: $h = 1, 2, \ldots, |E|$

(c) Assuring that aggregate flows on intersecting edges e_h and $e_{h'}$ are assigned different channels:

$$\sum_{r=1}^{|D|} x_{r,h}^l + \sum_{r=1}^{|D|} x_{r,h'}^l \leq 1 \qquad (6)$$

for each pair of intersecting edges e_h and $e_{h'}$;
$l=1,2,\ldots,\Lambda$; $h=1,2,\ldots,|E|$; $h'=1,2,\ldots,|E|$;

Constraint (4) guarantees formation of a single transmission path for each pair of demand end nodes p and q, based on Kirchhoff's law. Formula (5) is to assure that the total flow assigned to edge e_h will not exceed the maximum capacity available at e_h at time t. Formula (6) provides assignment of different channels to intersecting links by checking that at most one link from the set of interfering links is assigned a given channel l. The objective is to minimize the aggregate cost of paths in terms of the aggregate signal attenuation calculated for all paths at time t, given by Eq. 3.

3.2 Computational complexity of WRLF problem

In this section, we prove that the considered optimization problem (3)–(6) of weather-resistant wireless links formation—WRLF—is *NP*-complete. For this purpose, we will show that one of its subproblems, i.e., the channel assignment problem (WR_CAP), is *NP*-complete, meaning that no efficient algorithm has been invented so far to find the optimal solution in polynomial time.

Since we are interested in assigning the transmission channels to network links using at most Λ available channels, where Λ can be any arbitrary small integer value, optimization version of WR_CAP channel allocation subproblem can be defined as follows:

WR_CAP$_{opt}$(E')

Given the set of network edges E' utilized by paths from Step 2 of Algorithm 1, find the optimal assignment of transmission channels to edges e_h minimizing the number of used channels, providing that none of intersecting edges receives the same channel from the set of Λ available channels.

Following [36], in order to prove *NP*-completeness of WR_CAP optimization problem, we can do this for its recognition version (i.e., a problem with "yes" or "no" answer), defined as follows:

WR_CAP$_{rec}$(E', k)

Given the set of edges E' utilized by paths from Step 2 of Algorithm 1, is it possible to find the optimal assignment of channels to edges e_h in the network that requires k different channels, providing that none of intersecting arcs receives the same channel?

Following [36], if a recognition version of the problem is *NP*-complete, so is its optimization version.

Theorem 1 WR_CAP_{rec} problem is *NP*-complete.

Proof Following [36], when proving the *NP*-completeness of WR_CAP problem, it is necessary to show that:

(a) $WR\_CAP_{rec}(E', k)$ belongs to the class *NP*,
(b) A known *NP*-complete problem polynomially reduces to $WR\_CAP_{rec}(E', k)$.

Ad a) The considered WR_CAP$_{rec}$ problem is in complexity class *NP*, since it can be determined in polynomial time whether a given assignment of transmission channels to edges e_h is valid (i.e., whether it uses exactly k different channels from set 1, ..., Λ, as well as satisfies the constraints concerning intersecting links). All that is needed is to check channels assigned to arcs by performing $O(|E'|) \leq O(|n^2|)$ operations, as well as to check whether different channels are assigned to each pair of intersecting links (also requiring at most $O(|n^2|)$ operations).

Ad b) In order to provide the second part of the proof, we will show that the *NP*-complete problem of determining the optimal *vertex-coloring* of a *graph of conflicts G* described in [36], here referred to as VCGC, can be transformed in polynomial time to WR_CAP problem.

Recognition version of VCGC problem is defined as follows [36]:

VCGC$_{rec}$(G, k)

Given a graph of conflicts G=(V, L), where V denotes the set of vertices, while L denotes the set of arcs $l_h = (i, j)$ representing conflicts between the respective vertices i and j, is it possible to find the optimal assignment of colors to vertices from V requiring exactly k colors in a way that any two conflicting vertices i and j (i.e., connected by an arc in G) receive different colors?

Assume that:

- $\{G=(V, L), k\}$ is the input to the $VCGC_{rec}$ problem instance,
- G also represents a graph of conflicts for links to be installed in the wireless mesh network after executing Step 2. In particular, in this graph:
  - vertices from V represent links to be installed in the network,
  - there exists arc $l_h = (j, k)$ in G, if the respective network edges e_j and e_k intersect with each other, i.e., if they have to be assigned different transmission channels.

(⇒): Let us assume that it is feasible to color the vertices of G in the $VCGC_{rec}(G, k)$ problem using k different colors. In this case, any valid coloring of G by means of k colors automatically gives a proper assignment of k different channels to interfering wireless links in $WR\_CAP_{rec}(E', k)$ problem. (⇐): Assume that k different channels are sufficient to find the solution to the $WR\_CAP_{rec}(E', k)$ problem. This assumption implies that after creating the respective graph of conflicts G for interfering links, we automatically have a valid coloring of G vertices that uses k colors. □

It is worth noting that even if we disregard the requirement on allocation of different channels to intersecting links in our WR_CAP problem, the simplified version of this problem is still *NP*-complete, since it remains the basic problem of finding the transmission paths between $|D|$ pairs of end-nodes in capacity-constrained networks (shown to be *NP*-complete in [37]). Therefore, to perform Step 2 of our algorithm, in simulations we use heuristic Dijkstra's algorithm [38,39] for path calculations.

3.3 Example execution of the algorithm

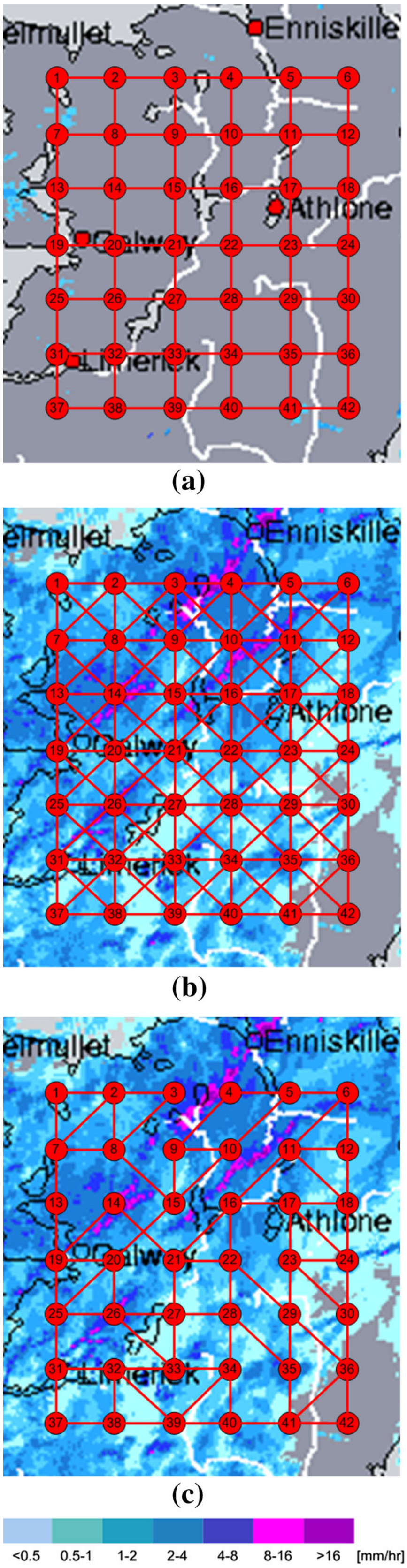
Figure 3 presents a single iteration of the proposed algorithm execution. Before running the algorithm, initial alignment of antennas is as given in Fig. 3a. However, based on information on current radar rain map from Fig. 3b, topology of the network needs to be updated to become prepared for the forthcoming rain. The respective core node responsible for determining the updates of a network topology first extends the topology from Fig. 3a to include all links between neighboring WMN nodes[1] (see Fig. 3b). After that, based on forecasted attenuation of a signal along each possible link, new alignment of antennas is determined (see Fig. 3c). In the considered example, the updated topology from Fig. 3c does not include links located within heavy rain storm areas (e.g., links (`3, 4`), (`10, 11`), (`14, 15`), and (`15, 16`)).

4 Simulation analysis

In this section, we include analysis of simulation results obtained to verify characteristics of our approach for two example artificial 42-node WMN topologies shown in Fig. 4, proposed for the areas of Southern England and Ireland, accordingly. Topology of each network was defined by a 6 × 7 grid structure, where length of each link was equal to 15 km.

Characteristics of our approach (called "with protection" in this section) were compared with the respective common one (i.e., implying no changes in the alignment of antennas), further referred to as the "no protection" case. In our approach, the initial set of WMN links comprised the ones marked with solid red lines in Fig. 4. Dashed blue lines in Fig. 4 were used to indicate the extension of the set of links for possible utilization. In the reference "no protection" approach, configuration of network links did not change over time (i.e., it was determined only by solid red lines from Fig. 4).

In each analyzed network, nodes `1` and `42` were used as gateways connecting the remaining ones to the Internet. Traffic outgoing the network via one of two assumed gateways was generated by each network node at a rate of 3 Mbps. During simulations, we measured the average signal attenuation ratio due to rain storms along transmission paths, as well as the average path hop count. In particular, with respect to the first investigated parameter, we analyzed the ratio of signal attenuation reduction obtained by our approach, compared to



(a)

(b)

(c)

Fig. 3 Example execution steps of Algorithm 1 to modify the topology of the Irish Network according to the rain storm forecasts

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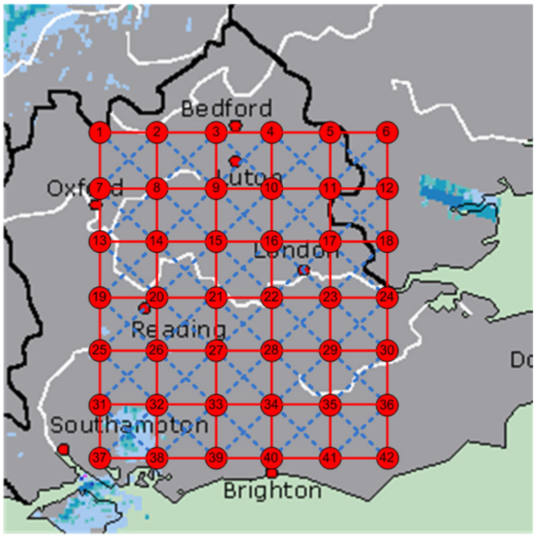
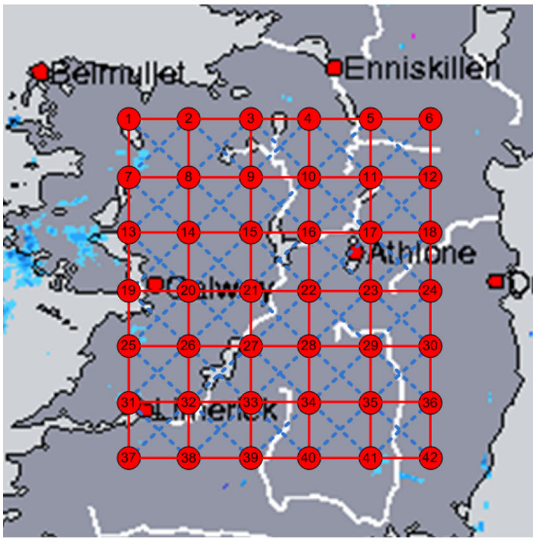
[1] A procedure of WMN neighboring nodes discovery can be found e.g., in [40].



(a) Sothern English Network



(b) Irish Network

Fig. 4 Example topologies of WMNs used in simulations

the results of the common case of not changing the alignment of antennas.

In simulations, we used weather data from the following three scenarios of real rain storms that occurred in the last decade of November 2011:

- Scenario A: Southern England, November 25, 2011, from 3:00 AM to 10:00 AM
- Scenario B: Ireland, November 26–27, 2011, from 8:00 PM to PM 7:00 AM
- Scenario C: Ireland, November 24, 2011, from 10:00 AM to 12:00 PM

Radar echo rain maps used in simulations were provided by http://www.weatheronline.co.uk service. They were recorded every 15 min. Duration of analyzed rain storms (calculated as the time difference between the last and the first observed signal attenuation along any WMN link), varied from 7 to 14 h. A limited set of analyzed rain maps (one map per hour) is shown in the Appendix in the later part of this paper.

4.1 Signal attenuation

In this section, we evaluate the properties of the proposed approach in terms of the level of signal attenuation during rain storms. In particular, we investigate the average decrease of signal attenuation, compared to the respective results obtained for the common "no protection" technique.

As expected, during heavy rain periods, the level of signal attenuation was remarkably increased. However, owing to periodic updates of antenna alignment according to the forecasted level of signal attenuation, we were able to decrease the signal attenuation up to 90 % (see Fig. 5). A general observation is that the greatest improvement was achieved for periods of heavy rain (which is indeed a very desired feature).

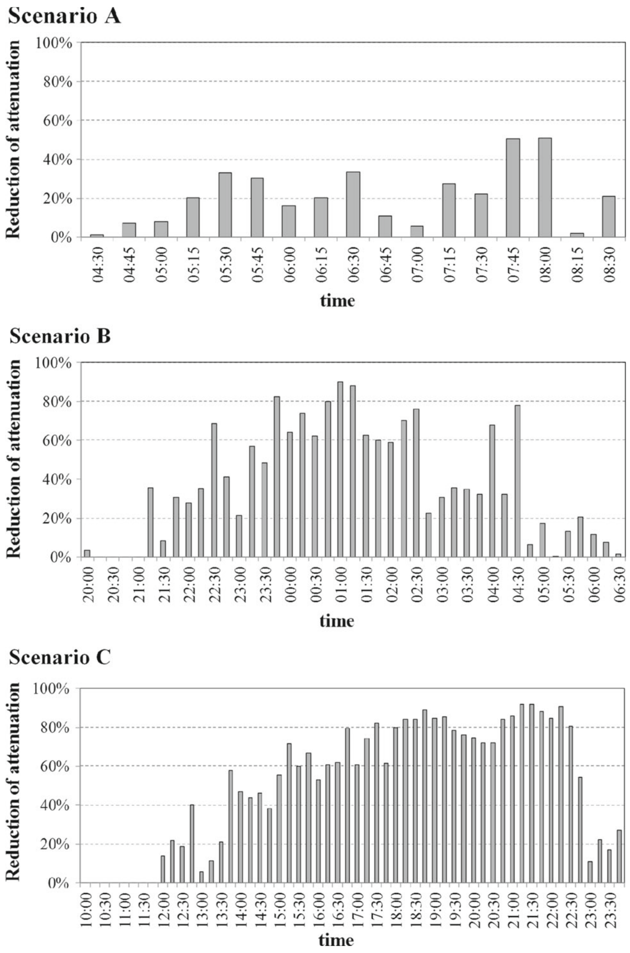


Fig. 5 Obtained decrease of signal attenuation

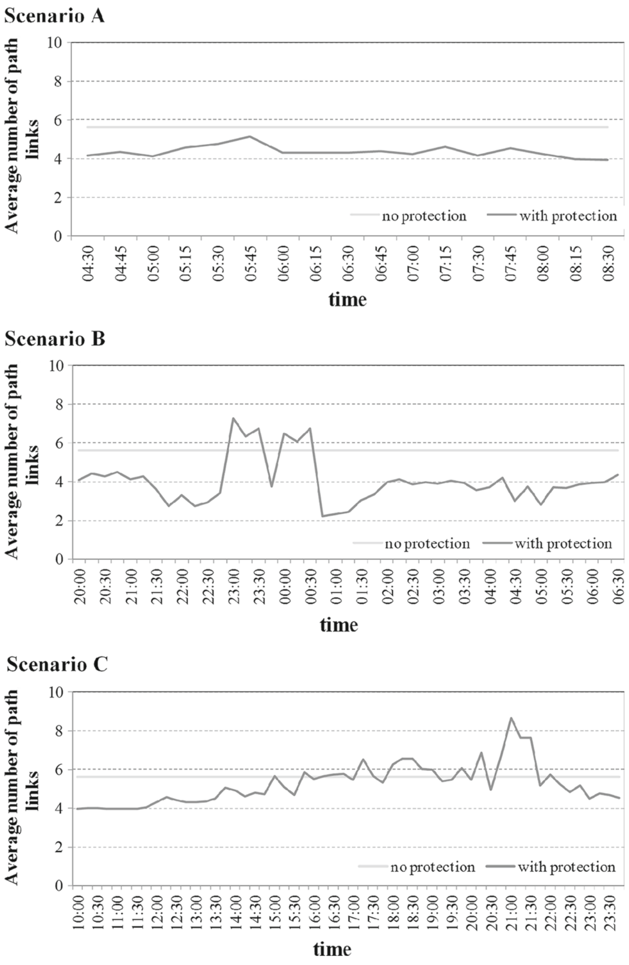


Fig. 6 Average hop count of transmission paths

On the contrary, in no-rain periods, there was practically no need to update the alignment of antennas. In the intermediate case of light rains, updating the alignment of antennas implied a slight decrease of the considered signal attenuation ratio.

4.2 Number of path links

Experiments were also performed to evaluate the average hop count of transmission paths from source nodes to gateway nodes. In the case of the common "no protection" method (for which the costs of links were independent of signal attenuation ratio), the number of path links (hop count) was equal to 5.6.

In our approach, due to allowing for formation and removal of links as a result of changing attenuation conditions, links were established in a more elastic way. For instance, this could imply forming diagonal links (e.g., between nodes `1` and `8`), which in general could lead to finding shorter paths (i.e., a single diagonal link could replace two consecutive non-diagonal links). Indeed, as shown in Fig. 6, the average number of path links obtained by our technique was often remarkably lower than the one for the reference approach.

However, in heavy rain periods (see Scenario B, 10 PM–1 AM, and Scenario C: 4 PM–10 PM), the average number of path links was greater owing to the necessity of introducing detours over heavy rain areas.

5 Conclusions

In this paper, we addressed the problem of signal attenuation in wireless mesh networks due to heavy rain storms. Special focus was put on weather disruptions occurring in bounded areas, leading to partial/full degradation of the effective capacity of communication links.

In order to improve the network performance during heavy rain periods, we introduced a method to perform in advance the periodic updates of a network topology based on information related to the forecasted areas of heavy rain achieved from radar echo rain measurements. Our approach is easily applicable in practice, since functionality of a dynamic antenna alignment is currently available in a number of commercial products. Another advantage towards easy deployment is that our approach leaves characteristics of any routing algorithm unchanged.

Advantages of the proposed technique, verified by means of simulations performed for real radar rain maps, include a significant reduction of signal attenuation (up to 90 % during simulations), compared to the characteristics achieved for the reference technique assuming no topology changes. It is worth noting that the greatest improvement was achieved for heavy rain periods, which is a very desired feature. In periods of light or moderate rain, our approach additionally results in establishing shorter transmission paths, implying lower values of propagation delay.

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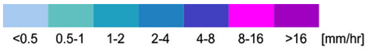
Appendix: rain radar maps used in simulations

This appendix contains rain radar maps from http://www.weatheronline.co.uk/ service recorded every 15 minutes (presented here in 1 h interval) used in simulations.

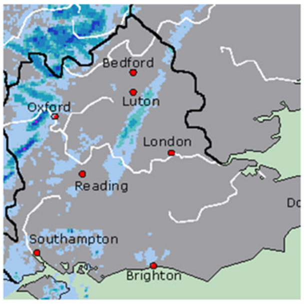
Each map, presented in this appendix, was created according to the following intensity scale:



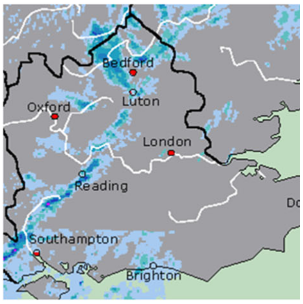
Scenario A: Southern England, November 25, 2011

3:00 AM

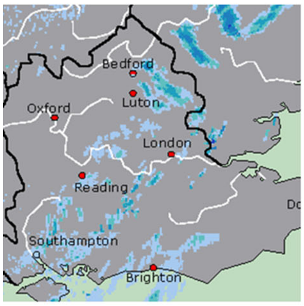
4:00 AM



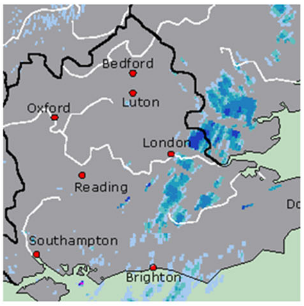
5:00 AM



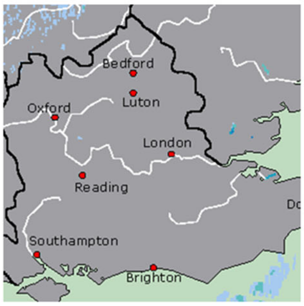
6:00 AM



7:00 AM



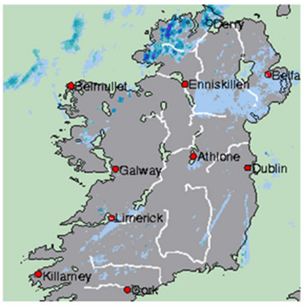
8:00 AM



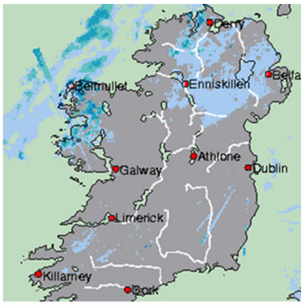
9:00 AM

10:00 AM

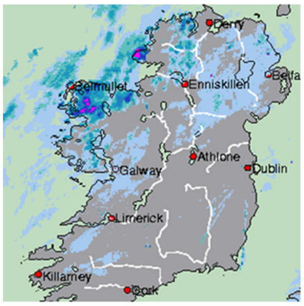
Scenario B: Ireland, November 26-27, 2011



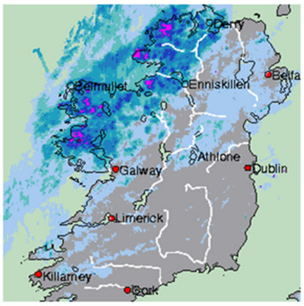
8:00 PM



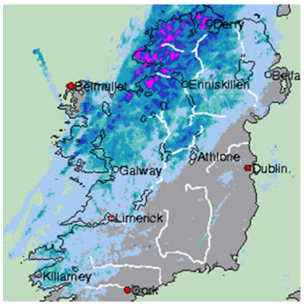
9:00 PM



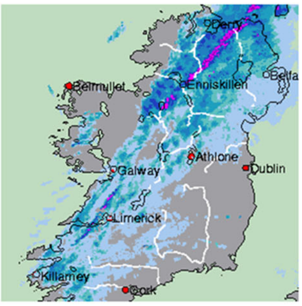
10:00 PM



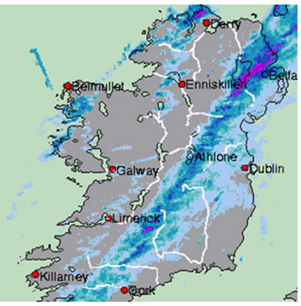
11:00 PM



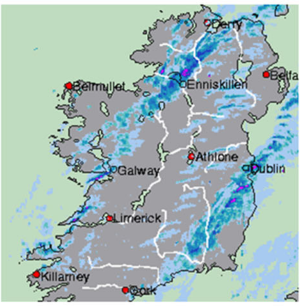
0:00 AM



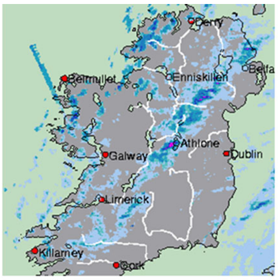
1:00 AM



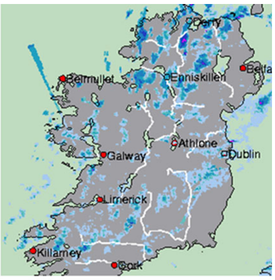
2:00 AM



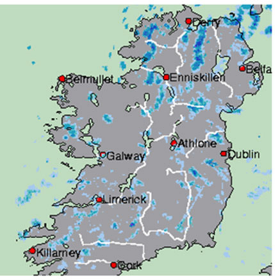
3:00 AM



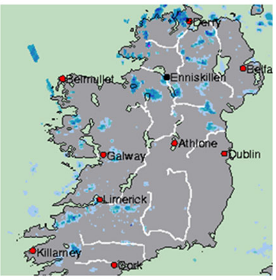
4:00 AM



5:00 AM

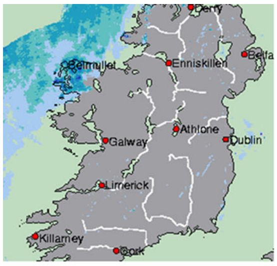


6:00 AM

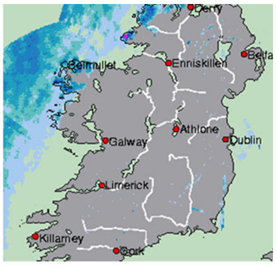


7:00 AM

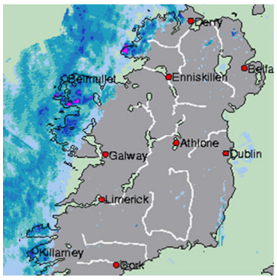
Scenario C: Ireland, November 24, 2011



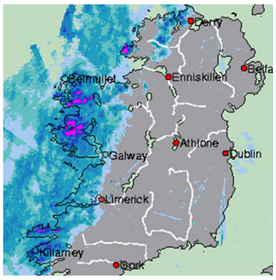
10:00 AM



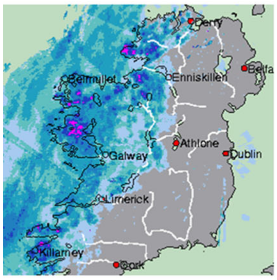
11:00 AM



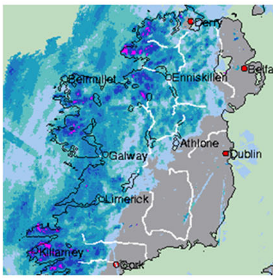
12:00 AM



1:00 PM



2:00 PM



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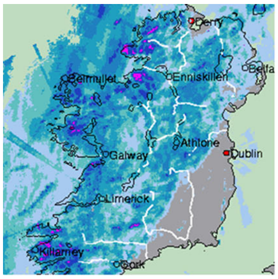

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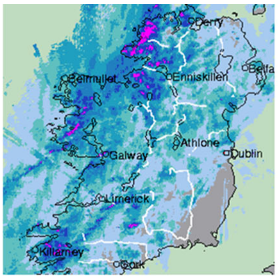

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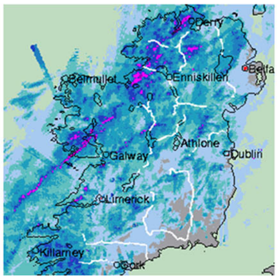

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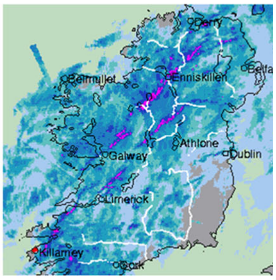
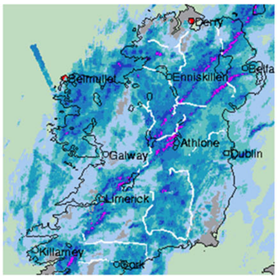
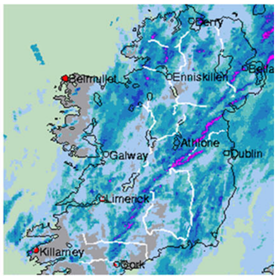


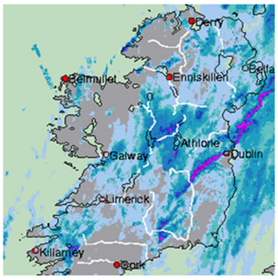
7:00 PM



8:00 PM



9:00 PM



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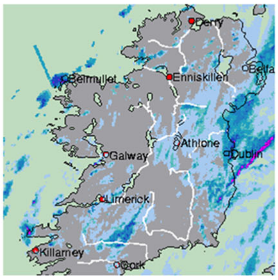

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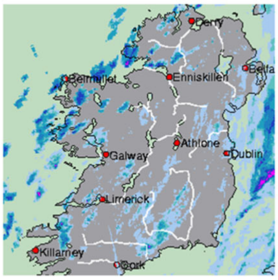

12:00 PM

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