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Contents

1 Introduction to the Algorithm Package

This Deliverable presents algorithmic implementations of the optimization models and procedures described in Deliverable D1.1. The implementation has been carried out using Python 2.7 [2], and the solver GUROBI [1] is called to solve mixed integer programming models. All codes are included in the Algorithm package. Below we give a brief explanation about this package.

- The file folder “topologies” includes the data set which will be used for the sequel experiments.
- The functions in readData.py are listed below.
  - datainput(): read the data about modulation and coding schemes, network topologies, path loss and directional antenna gain from the data files.
- The functions in models.py are listed below.
  - LS(): finding minimal frame length by joint optimization of transmission scheduling, routing and rate adaptation.
  - LS_RPC(): finding minimal frame length by joint optimization of transmission scheduling, routing, rate adaptation and power control.
  - LS_DRPC(): finding minimal frame length by joint optimization of transmission scheduling, routing, rate adaptation and power control under directional antennas.
  - primal_LS(): primal problem for joint optimization of transmission scheduling, routing and rate adaptation.
  - primal_LS_integer(): changing variables in primal_LS() from continuous to integers.
  - primal_routing_integer(): changing variables in primal_routing() from continuous to integers.
  - newComptibleSet(): finding an optimum compatible set with rate adaptation.
  - newComptibleSet_powerControl(): finding an optimum compatible set with rate adaptation and power control.
  - newComptibleSet_directional(): finding an optimum compatible set with rate adaptation and power control under directional antennas.
  - dynamic_channel(): finding minimal frame length by dynamic channel assignment.
  - static_channel(): finding minimal frame length by static channel assignment.
- The functions in ResourceAllocation.py are listed below.
  - entry_LS_M1(): the main function for minimizing frame length by joint optimization of transmission scheduling and routing with only one modulation and coding scheme.
  - entry_LS(): the main function for minimizing frame length by joint optimization of transmission scheduling, routing and rate adaptation.
  - entry_LSRAPC(): the main function for minimizing frame length by joint optimization of transmission scheduling, routing, rate adaptation and power control.
  - entry_DA(): the main function for minimizing frame length by joint optimization of transmission scheduling, routing, rate adaptation and power control under directional antennas.

  - entry_dynamic_channel(): the main function for finding minimal frame length by dynamic channel assignment.
  - entry_static_channel(): the main function for finding minimal frame length by static channel assignment.

- The functions in MMF.py are listed below.
  - primal_MMF(): the primal problem for maximizing the minimal flow.
  - MMF_omni_LS_M1(): maximizing the minimal flow by joint optimization of transmission scheduling and routing with only one modulation and coding scheme.
  - MMF_omni_LS(): maximizing the minimal flow by joint optimization of transmission scheduling, routing and rate adaption.
  - MMF_omni_PC(): maximizing the minimal flow by joint optimization of transmission scheduling, routing, rate adaption and power control.
  - MMF_directional(): maximizing the minimal flow by joint optimization of transmission scheduling, routing, rate adaption and power control under power control.
  - entry_MMF(): the main function for calling different functions for maximizing minimal flow.

- The functions in MetricRouting.py are listed below.
  - metricRouting(): finding optimal link metrics.
  - entry_metric(): the main function for finding optimal link metrics.

2 A Numerical Study on a Realistic Topology

In this section, optimal solutions of the optimization models in Deliverable D1.1 [4] are illustrated using the algorithm package. The mesh network shown in Figure 1, which is an experimental metropolitan wireless multi-radio mesh network in the city of Heraklion, Greece, deployed by FORTH [3], has been used. Nodes K1-K6 are mesh routers. Among them, K1 and K4 are gateways. In this illustration, K1 is taken as the gateway for all other nodes to demonstrate optimal solutions. The blue lines represent undirected radio links within the mesh network. The links are summarized in Table 1, where the length of each link is provided. During the computation, each undirected link will be converted to two oppositely directed links.

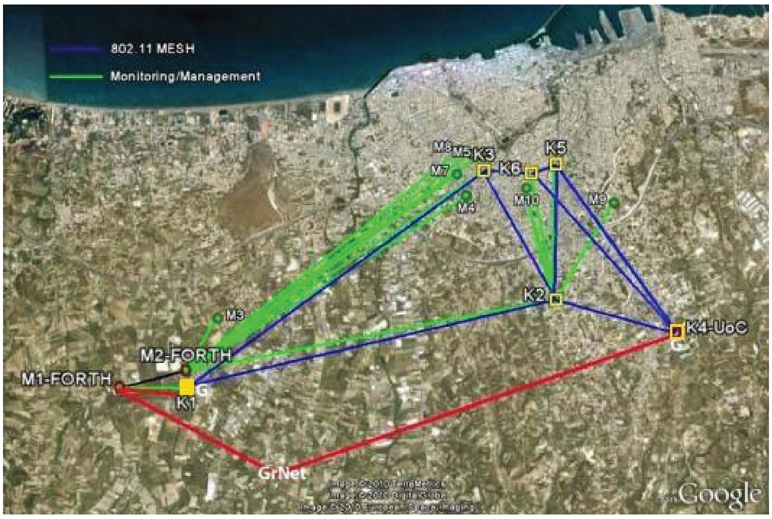


Figure 1: FORTH's updated metropolitan mesh network.

Table 1: The set of links.

link	distance (Km)	link	distance (Km)
(K1,K2)	5.1	(K4,K6)	3.6
(K1,K3)	4.9	(K5,K2)	2
(K2,K3)	2.0	(K5,K6)	0.4
(K4,K2)	1.6	(K6,K3)	0.8
(K4,K5)	3.3		

The mesh network works with IEEE 802.11g and uses OFDM PHY on the 2.4GHz band. The channel model, shown in equation (1), is used to compute the path loss [5]. In the equation, p_{vw} (in dB) is the power received at node w from node v, p_v (in dBW) is the transmission power of node v and d_{vw} (in m) is the distance between the two nodes.

$$p_{vw} = p_v - 30 - 20 \cdot \log d_{vw} \tag{1}$$

For the experiments, the maximum transmission power for each node is 100 mW, and the noise power is $\eta = 7.96^{-11}$ W. The set of modulation and coding schemes (MCSs) consists of BPSK 1/2, BPSK 3/4, and QPSK 1/2.

2.1 Resource Allocation Driven by Minimum-length Scheduling

Optimization algorithms for optimal allocating resources driven by minimum-length scheduling (see also Section 3 of Deliverable D1.1) have been tested. First, the optimal solution by joint optimizing link scheduling, routing and link rate adaptation are presented. Then the power control mechanism and directional antennas are deployed to improve further the frame length. At last, by applying multiple channels, its impact on the frame length is investigated. It is assumed that the demand for each mesh router, i.e., node K2, K3, K5, K4, and K6, is 100 Mb. Each mesh router can download traffic from the gateway K1.

The model for jointly optimizing link scheduling, routing and link rate adaptation consists of a master problem (model (7) in Deliverable D1.1) and a pricing problem (model (9) in Deliverable D1.1). To solve the model efficiently using the column generation method, the linear relaxation of the master problem is considered. Then, utilizing the obtained list of compatible sets, the master problem is re-solved with integer variables in order to deliver the integer solution.

The solution is shown in Table 2, where an optimal list of compatible sets is presented. In a compatible set, each link is associated with a date rate, corresponding to the selected MCS. As shown in the table, the optimal frame length for this scenario is 64 time slots.

Table 2: Optimal link scheduling, routing and rate adaptation.

#	compatible sets {link,rate}	time slots
1	{(2,4),12} {(3,6),6}	9
2	{(2,5),12}	9
3	{(3,6),12}	4
4	{(1,2),12}	25
5	{(1,3),12}	17

Next, the power control mechanism is introduced, that is, the transmission power for each node can be adjusted from one time slot to another. The transmission power is limited by the maximum transmission power of 100 mW. In this case, the master problem keeps the same, i.e., model (7) in Deliverable D1.1. The pricing problem is changed to model (11) in Deliverable D1.1.

The optimal solution for joint optimizing link scheduling, routing, rate adaptation, and power control is shown in Table 3. As can be observed, the power levels for some of the mesh nodes are very small; this saves energy and limits the interference to other nodes. Hence the spatial reuse is further improved, and the frame length is reduced by 5 time slots, to 59 time slots.

Table 3: Optimal link scheduling, routing, rate adaptation, and power control.

#	compatible sets {link,rate, power}	time slots
1	{(2,4),6, 1} {(3,6),12, 2}	17
2	{(1,2),12, 100} {(6,5),12, 3}	17
3	{(1,3),12, 8}	25

To investigate the benefits of using directional antennas, the configuration is modified, such that all nodes deploy directional antennas. The antenna pattern is shown in Figure 4 of Deliverable D1.1. The peak gain is 5 dBi and the beam width is 120°.

Table 4 shows the optimal solution for joint optimization of link scheduling, routing, rate adaptation, and power control, with directional antennas. The optimal frame length is now 48 time slots, which is much smaller than the case with omni-directional antennas.

Table 4: Optimal solution corresponding to directional antennas.

#	compatible sets {link,rate, power}	time slots
1	{(4,5),12,1}	5
2	{(1,3),12,100} {(2,4),12,26}	14
3	{(1,2),6,100} {(3,6),12,18}	2
4	{(1,3),12,3} {(6,5),12,0.1}	6
4	{(1,2),12,15} {(3,6),6,1}	21

Finally, the case of multiple available channels is considered. The maximum number of interfaces in each node is assumed to be four, and the number of orthogonal channels is set to be three. Utilizing the compatible sets in Table 4, the optimal solution of dynamic and static channel assignment are given in Table 5 and Table 6, respectively. It is observed that dynamic channel assignment requires only 21 time slots as the frame length, giving a significant improvement in relation to the that obtained by using directional antennas. The optimal solution of static channel assignment requires two more time slots, i.e., 23 time slots. Thus static assignment, which is more easy to deploy, carries only a small performance loss.

Table 5: Dynamic channel assignment.

#	{compatible set,channel}	time slots
1	{{(1,3),12}, {(6,5),12}}, 1 {{(1,2),12}, {(3,6),6}}, 2	1
2	{{(4,5),12}},1 { {(1,2),12,2},{(3,6),6} },2	3
3	{{(1,3),12},{(2,4),12}},1 {{(1,2),12}, {(3,6),6}},2	6
4	{{(1,2),12},{(3,6),6} },1	2
5	{{(1,3),12},{(2,4),12}},1 {{{(1,3),12}, {(6,5),12},2 {{(1,2),12},{(3,6),6}},3	5
6	{ {(4,5),12}},1 {{(1,3),12}, {(2,4),12}},2 {{(1,2),12},{(3,6),6}},3	2
7	{{(1,3),12},{(2,4),12}},1 {{(1,2),6},{(3,6),12}},2 {{(1,2),12},{(3,6),6}},3	2

Table 6: Static channel assignment.

#	{compatible set,channel}	time slots
1	{{(1,3),12},{(2,4),12}},2 {{(1,2),12}, {(3,6),6}},3	10
1	{{(1,3),12}, {(6,5),12}}, 2 {{(1,2),12}, {(3,6),6}}, 3	5
2	{ {(1,2),12,2},{(3,6),6} },3	2
2	{ {(1,2),6,2},{(3,6),12} },3	1
6	{ {(4,5),12}},1 {{(1,3),12}, {(2,4),12}},2 {{(1,2),12},{(3,6),6}},3	4
6	{ {(4,5),12}},1 {{(1,2),6}, {(3,6),12}},3 {{(1,3),12},{(6,5),12}},2	1

2.2 Max-min Flow Fairness

While applying the algorithm package to max-min flow fairness, the time duration is set to $T = 1$ s. The max-min flow is computed by jointly optimizing scheduling, routing, rate adaptation, and power control, for omni-directional antennas and directional antennas, respectively.

Algorithmic computations outlined in Algorithm 1 of Deliverable 1.1 have been implemented to compute the max-min flow. For omnidirectional antennas, the pricing problem for model (17) in Deliverable D1.1 is joint optimization of scheduling, rate adaptation, routing, and power control under omnidirectional antennas, i.e., model (11) in Deliverable D1.1. The optimal max-min flow vector is $f = (1.71, 1.71, 1.71, 1.71, 1.71)$, and the optimal solution is shown in Table 7.

For directional antennas, the pricing problem corresponding to directional antennas, shown in model (13) in Deliverable D1.1, is used. The max-min flow vector is $f = (2.12, 2.12, 2.12, 2.12, 2.12)$, and the optimal solution is shown in Table 8.

As one can observe from the results, the max-min flow obtained with directional antennas is bigger than that obtained with omnidirectional antennas.

Table 7: Optimal solution for max-min flow under omni-directional antennas.

#	compatible sets {link,rate, power}	time proportion
1	{(1,2),12,7,5} {(5,6),12,2}	7.1%
2	{(1,3),12,8}	42.9%
3	{(2,4),6,45} {(3,6),12,100}	28.6%
4	{(1,2),12,39}{(6,5),12,1}	21.4%

Table 8: Optimal solution for max-min flow under directional antenna.s

#	compatible sets {link,rate, power}	time proportion
1	{(1,3),12,100} {(2,4),6,13} {(6,5),12,3}	41.2%
2	{(1,2),12,100} {(3,6),6,8}	47.1%
3	{(2,5),12,100}	8.8%
4	{(4,6),12,1}	2.9%

2.3 Metric-driven Routing Design

Finally, the optimal solution of adapting link metrics for maximizing the minimal flow based on the compatible sets in Table 7 and in Table 8, respectively, is illustrated. For metric-driven routing, the upper bound for the link metric K in model (18) of Deliverable D1.1 is set to be 10 and the time duration T is 1.

For omni-directional antennas, the maximal-minimum flow of metric-driven routing is 1.71 Mbps, which is the same as the value obtained by in Section 2.2. The optimal link metrics are shown in Table 9. The routing paths for each mesh router is the shortest path from the gateway to the corresponding destination with respect to the optimal link metrics. These optimized paths are $K1 \to K2$, $K1 \to K3$, $K1 \to K2 \to K4$, $K1 \to K3 \to K6 \to K5$, and $K1 \to K3 \to K6$.

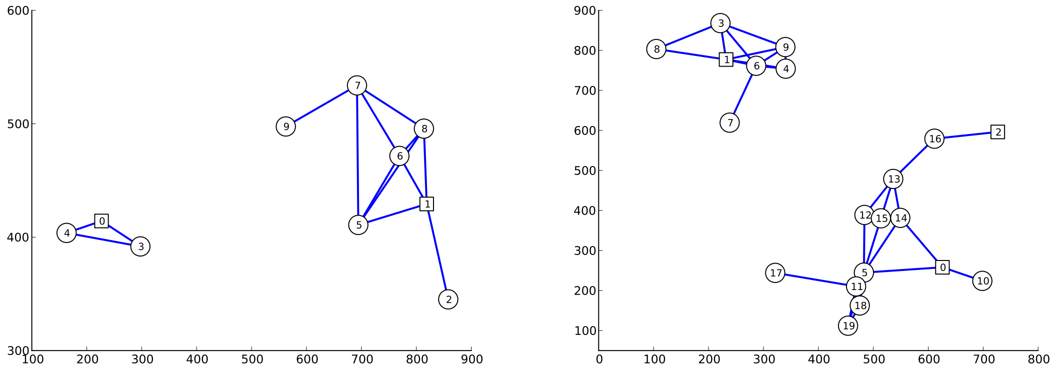
Table 9: Optimal link metrics for the case of omni-directional antennas.

link	metric	link	metric	link	metric	link	metric
(K1,K2)	1	(K2,K5)	4	(K4,K2)	1	(K5,K4)	1
(K1,K3)	1	(K3,K1)	1	(K4,K3)	1	(K5,K6)	1
(K2,K1)	1	(K3,K2)	1	(K4,K5)	1	(K6,K3)	1
(K2,K3)	2	(K3,K4)	3	(K4,K6)	1	(K6,K4)	3
(K2,K4)	2	(K3,K6)	1	(K5,K2)	1	(K6,K5)	1

For directional antennas, the maximal-minimum flow of metric-driven routing design is 2 Mbps, which is slightly smaller than the value obtained in Section 2.2. The optimal link metrics are shown in Table 10. The routing paths, again representing the shortest paths with respect to the optimized link metrics, are $K1 \rightarrow K2$, $K1 \rightarrow K3$, $K1 \rightarrow K2 \rightarrow K4$, $K1 \rightarrow K2 \rightarrow K5$, and $K1 \rightarrow K3 \rightarrow K6$.

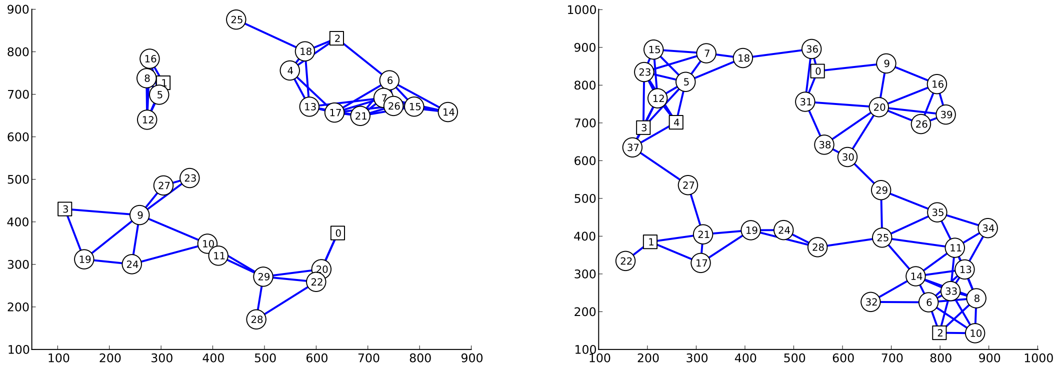
Table 10: Optimal link metrics for the case of directional antennas.

link	metric	link	metric	link	metric	link	metric
(K1,K2)	2	(K2,K5)	1	(K4,K2)	1	(K5,K4)	2
(K1,K3)	2	(K3,K1)	1	(K4,K3)	2	(K5,K6)	2
(K2,K1)	1	(K3,K2)	3	(K4,K5)	2	(K6,K3)	1
(K2,K3)	2	(K3,K4)	2	(K4,K6)	1	(K6,K4)	1
(K2,K4)	1	(K3,K6)	1	(K5,K2)	1	(K6,K5)	1



(a) 10 nodes, 2 gateways

(b) 20 nodes, 3 gateways



(c) 30 nodes, 4 gateways

(d) 40 nodes, 5 gateways

Figure 2: A set of random network examples.

3 A Numerical Study on Random Networks

In this section, a numerical study of applying the algorithm package to randomly generated network topologies is presented. The networks are generated by distributing nodes in a square area of 1000 m × 1000 m. The gateways are randomly chosen among the nodes. A link can be established between a pair of nodes if and only if the signal-to-noise ratio (SNR) condition is satisfied, i.e. $p_{vw}/\eta \geq \gamma$ where p_{vw} is the power received at node w from the transmitting node v, η is the noise power, and γ is the SINR threshold. The value of p_{vw} can be computed following the channel model (1). In all subsequent experiments, the noise power is $\eta = 7.96^{-11}$ W and the transmission power is 100 mW.

Figure 2 illustrates a set of random networks under the SINR threshold $\gamma = 3.5$ dB. Squares represent gateways and circles represent mesh routers. This figure only shows several examples for illustrative purpose, whereas a large set of random networks is generated in applying the algorithm package.

First, the minimal frame lengths for four different optimization setups: joint optimizing link scheduling and routing (JLR); joint optimizing link scheduling, routing and rate adaptation (JLRR); joint optimizing link scheduling, routing and power control (JLRRP); joint optimizing link scheduling, and routing and power control under directional antennas (JLRRPD), are computed and compared. In JLR, there is only one available MCS and it is assumed to be BPSK 1/2 with data rate

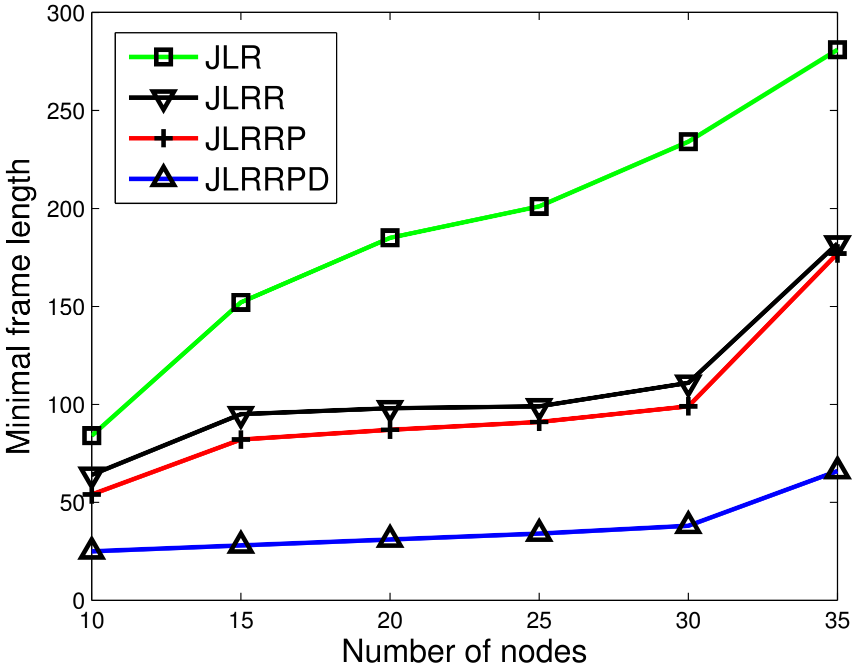


Figure 3: Comparison of frame length for various optimization setups.

6 Mbps and SINR threshold $\gamma = 3.5$ dB. For other optimization setups, all eight MCSs given in Table 1 of Deliverable D1.1 are considered. In JLRRPD, the adopted directional antenna is the same as one used in Section 2.1.

A comparison of the minimal frame lengths delivered by all the optimization setups are shown in Figure 3. The tested networks are divided into five groups, with $10, 15, 20, 25$, and 30 nodes respectively. For each group, 10 instances are tested and the average result is plotted in the figure. As can be observed, rate adaptation, the power control, and directional antennas can help reduce the frame length.

Figure 4 demonstrates the difference between static channel assignment and dynamic channel assignment (abbreviated as SCA and DCA, respectively, in the figure) for random networks.

The compatible sets used for channel assignment in generated by JLR. As can be observed, dynamic channel assignment saves many time slots in comparison to static channel assignment when the number of nodes grows.

Next, the minimal flow (i.e., the optimal flow found in the first step of Algorithm 1 in Deliverable D1.1) for various combinations of link scheduling, routing, rate adaptation, power control, and directional antennas is considered. The results are shown in Figure 5 where the tested networks are the same as those used to produce Figure 3. As expected, the minimal flow among all mesh routers decreases in the number of nodes, and increases when there is additional degrees of freedom become available.

Finally, the algorithm package is applied to link metric design for random networks. The metric-driven routing is compared with the globally optimized routing and shortest-hop routing. The globally optimized routing refers to the routing derived from the multi-commodity flow model, without the restriction that the paths must be the shortest ones in respect of the link metrics. The shortest-hop routing refers the case where the routing for each mesh router is the shortest path in the number of hops (i.e., the special case of metric-driven routing with one as the metric for all

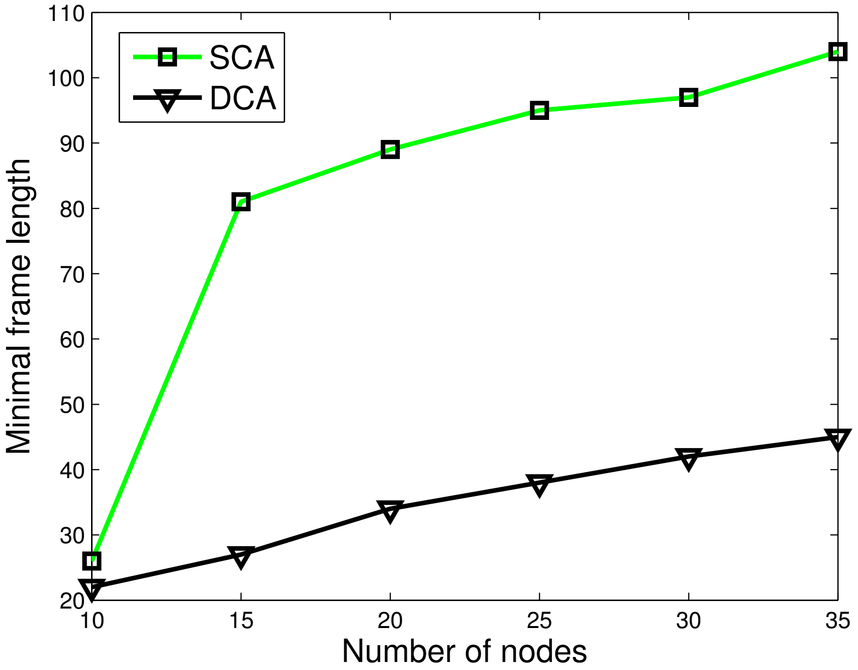


Figure 4: Comparison of static and dynamic channel assignment

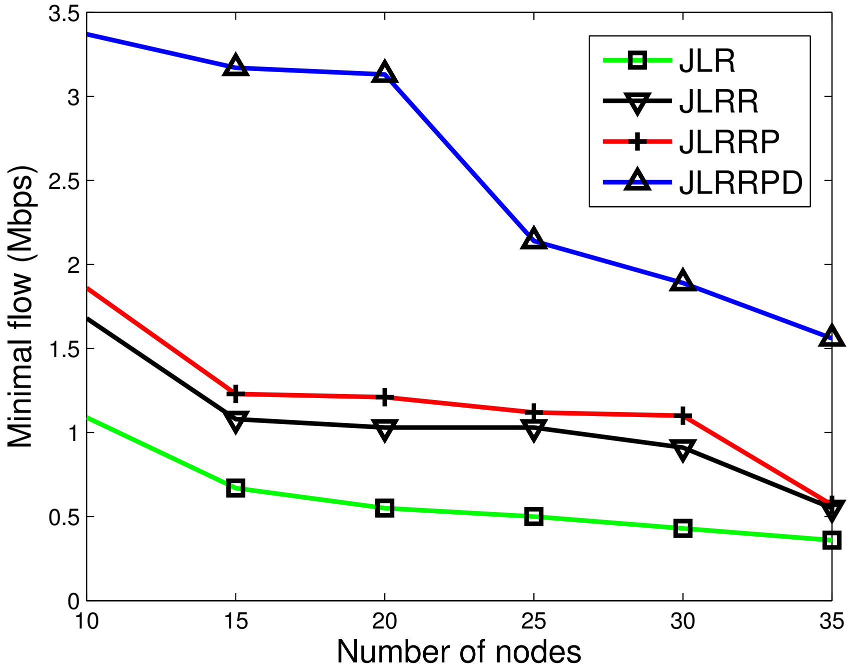


Figure 5: Comparison of minimal flow for different optimization models

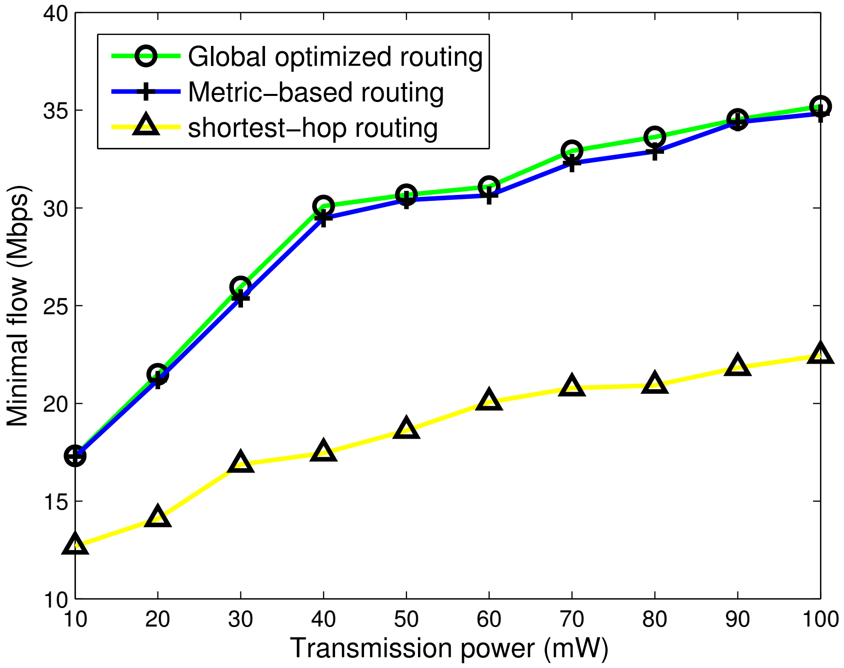


Figure 6: Comparison of metric-driven routing with others.

Table 11: Optimal link metrics for a random network.

link	metric	link	metric	link	metric	link	metric
(1,4)	2	(4,5)	8	(7,8)	1	(9,6)	1
(1,5)	1	(5,4)	2	(7,9)	2	(9,7)	8
(2,3)	1	(6,7)	9	(8,6)	1	(9,8)	3
(2,6)	2	(6,8)	2	(8,7)	1	(10,8)	1
(2,7)	1	(6,9)	2	(8,9)	1		
(2,9)	2	(7,6)	1	(8,10)	1		

links).

In the computational experiment, the compatible sets used for metric-driven routing is obtained from JLR. Ten instances of random networks of 10 nodes are considered for computing the average minimal flow. Figure 6 gives the variation of the average minimal flow in the transmission power. As shown in this figure, the optimal minimum flow obtained by the metric-driven routing is just slightly smaller than that of the globally optimized routing, but much large than that of shortest-hop routing. It is also of significance to observe that the gap between the metric-driven routing and the shortest-hop routing gradually increases as the transmission power increases.

To illustrate the optimal link metrics, the random network in Figure 2(a) is used as an example. Omni-directional antennas are used in this case and the optimal minimum flow is 2.25 Mbps. The corresponding optimal link metrics are shown in Table 11.

4 Conclusions

This deliverable has presented the algorithm package for mesh network capacity optimization. The package contains solution procedures for the mathematical optimization formulations provided in Deliverable 1.1, for optimal scheduling with rate adaptive, channel assignment, max-min fairness, and metric-driven routing. The application of the developed optimization procedures has been illustrated by using the package for optimizing a realistic mesh network in the city of Heraklion, Greece, as well as random networks. The results demonstrate the usefulness of mathematical optimization for performance characterization of wireless mesh networks.

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