Network Planning for the Future Railway Communications

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***Abstract*—Smart transportation systems are changing the way future mobility is conceived. In particular, railways are undergoing a transformation process to modernize public transportation and rail operation. Technologies like 5G, optical fiber and cloud data centers have emerged as catalysts to digitalize the railway by providing high-speed and low-latency communications. In this work, the network planning for the future communications in long-distance rail systems is presented. This work introduces two mechanisms to solve the network planning problems in the future railway communications. First, the Base Station Placement Problem (BSPP) is solved, aiming at guaranteeing the necessary cell edge throughput along the rail tracks. Second, an integer linear program formulation is used to solve the Data Center Placement and Assignment Problem (DCPAP), where data centers are placed and optimally associated to the train stations, while reducing latency and costs. The obtained results show the trade-off between the average latency, the infrastructure costs, the optimal number of data centers and their location.**

***Index Terms*—network planning, railway communications.**

I. Introduction

Railway communications represent an active challenge for Rail Operators (ROs) across the globe. Today, the Rail Data Network (RDN) must cope with critical low-latency Digital Rail Operation (DRO) and bandwidth-hungry Passenger Connectivity (PC) services. DRO encompasses train operation and safety services with strict latency requirements for reporting information to the railway management system [1]. PC is an essential socio-economic driver, as offering stable on-board Internet access impacts passengers' choice in favor of trains.

TABLE I
Throughput and latency requirements in UpLink (UL) and DownLink (DL) for DRO and PC until 2030 in a train carrying up to 1000 passengers as estimated by Ericsson [1] and the European Rail Infrastructure Managers (EIM) [2].

Service	UL	DL	Latency
DRO	15 Mbps	300 kbps	10 ms
PC	$\leq$ 1 Gbps	1 Gbps	-

The Global System for Mobile Communications - Railway (GSM-R) is the communication standard in European rail management. However, the existing infrastructures based on GSM-R cannot cope with the requirements derived from DRO and PC, summarized in Tbl. I. GSM-R equipment will become obsolete by 2030 [2] and the standardization of its successor, the 5G-based Future Railway Mobile Communication System (FRMCS), is still ongoing.

Yan et al. [3] presented the challenges in train communications: the penetration losses of up to 30 dB due to the train's metal body and the group handovers triggered by User Equipments (UEs) moving across cells. In their work, Yan et al. proposed a network architecture consisting of a dual-frequency and cloud-based Radio Access Network (RAN), which shares similarities with the one proposed by Ai et al. [4]. In both works, Remote Radio Heads (RRHs) in the sub-6GHz band provide coverage for DRO and the control plane of PC, while RRHs in the mmWave band provide high throughput for the data plane of PC. Cloud-RAN (C-RAN) facilitates centralized management and enables inter-cell interference cancellation using Coordinated Multi-Point (CoMP) transmission. Nokia [5] proposed a two-level optical network architecture connecting the segments in the railway communication network. The first level is an optical access network connecting the RRHs in the RAN and the Train Stations (TSs). The second is a nationwide Core Network (CN) connecting the main TSs with the remote Data Centers (DCs).

This work focuses on a network planning solution enabling DRO and PC in future railway communications. For this, the following two-step methodology is presented: *i)* The Base Station Placement Problem (BSPP) uses a heuristic based on a 3GPP's propagation model, which finds the required number of Base Stations (BSs) and their location along the rail tracks while guaranteeing the required throughput at the cell's edge. *ii)* The Data Center Placement and Assignment Problem (DCPAP), modeled with an Integer Linear Programming (ILP) formulation that optimally places the DCs and associates TSs to DCs, while minimizing costs and latency.

This work is organized as follows: Section II presents the proposed network architecture. Section III describes the problem formulation. Section IV presents the evaluations and the results. Finally, Section V concludes this work.

II. Proposed Network Architecture

Fig. 1 depicts the proposed network architecture for future railway communications. Low-throughput but time-sensitive

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DRO data is sent to the nearest Macro BS (MaBS), while best-effort but high-throughput PC data is sent to the nearest Micro BS (MiBS). As depicted with the red and blue lobes, the Mobile Relay (MR) on the train's roof communicates with the dual-frequency RAN infrastructure. The MaBS and MiBS use the sub-6GHz and the mmWave bands, respectively. The MR distributes Internet services to on-board UEs, e.g., via WiFi Access Points (APs), which groups UEs as a virtual UE and simplifies handover procedures. UEs avoid signal attenuation problems caused by the train's metal structure, as they do not directly connect to the infrastructure along the rail tracks.

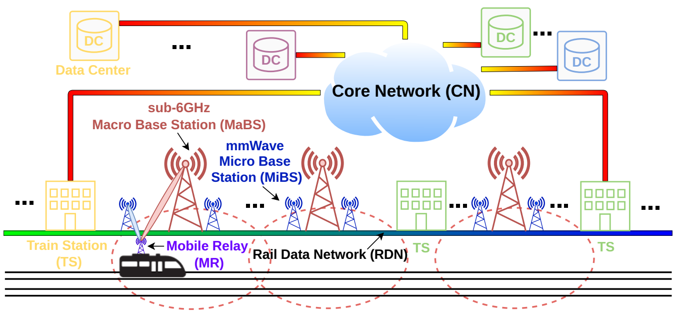


Fig. 1. Rail segments depicting the components and their interconnection in the proposed network architecture for the future railway communications.

As depicted with the dotted red ellipse in Fig. 1, each MaBS is associated with a set of MiBSs. A train may use multiple MiBSs inside the coverage area of a MaBS and these can be coordinated using CoMP according to the train's movement. A handover is triggered when a train leaves the coverage area of a MaBS. DRO and PC traffic from the BSs[1] is transmitted over the RDN to the nearest TS. The RDN includes the RAN and the the optical backhaul deployed by the RO along the rail tracks. As depicted with yellow and green colors, each TS is associated with a DC, where the RO's applications are stored. The main TSs connect to the CN and relay connectivity services to TSs, which are connected only to the RDN. The RO leases optical links in the CN from a network provider.

III. Problem Formulation

A. Base Station Placement Problem (BSPP)

BSPP dimensions the dual-frequency RAN while guaranteeing the throughput requirements at the cells' edge. The dual-frequency RAN is represented in Fig. 1 with red MaBSs and blue MiBSs. The BSPP plans the dual-frequency RAN using the heuristic in Alg. 1. This heuristic determines the upper-bound train transit frequency in each rail segment between two TSs and combines it with the throughput requirements per train of Tbl. I to have an upper-bound on the traffic requirements. With this information, the heuristic defines the coverage radius of the MaBSs and MiBSs using a 3GPP's propagation model following the parameters in Tbl. II and associates MiBSs with MaBSs using distance-based clustering.

[1]The term *BS* generically refers to a MaBS or MiBS.

Algorithm 1 Base station placement heuristic.

Require: Rail network, radio channel parameters (*param.*) and throughput (*tput.*) requirements for MaBS and MiBS.

Create graph *G(N,E)* with *N* TS and *E* rail segments
radius$_{\text{MaBS}}$ ← 3gpp_propag_model(param$_{\text{MaBS}}$, tput$_{\text{MaBS}}$)
radius$_{\text{MiBS}}$ ← 3gpp_propag_model(param$_{\text{MiBS}}$, tput$_{\text{MiBS}}$)
for *e* in *G*.get_edges() **do**
    list$_{\text{MaBS}}$ ← place_base_station(*e*, radius$_{\text{MaBS}}$)
    list$_{\text{MiBS}}$ ← place_base_station(*e*, radius$_{\text{MiBS}}$)
    for MaBS in list$_{\text{MaBS}}$ **do**
        G.add_node(MaBS)
        for MiBS in list$_{\text{MiBS}}$ **do**
            if MaBS.has_in_coverage_radius(MiBS) **then**
                G.add_node(MiBS)
                MaBS.associate(MiBS)
                list$_{\text{MiBS}}$.remove(MiBS)
return *G*   # RDN with optical links and RAN

The radio channel for the BSs was modeled in the function *3gpp_propag_model*, which uses the 3GPP's TR 38.901 rural macro Line-Of-Sight (LOS) propagation model for frequencies from 0.5 to 100 GHz [6]. The propagation model is used for MaBS and MiBS as it is compatible with the frequencies in the sub-6GHz and mmWave bands. An LOS model was selected for the MaBSs, as antennas are deployed at high altitudes and the few obstacles have a low altitude [7]. LOS is possible for the MiBSs, due to short distances between trains and the infrastructure along the rail tracks, and the beanforming capability of antennas [8]. The coverage radius of the BSs is computed as a function of the nominal Signal-to-Noise Ratio (SNR). The SNR is used instead of the Signal-to-Interference-plus-Noise Ratio (SINR) since it is assumed that the inter-cell interference of BSs is negligible due to mitigation techniques such as CoMP. Using Shannon's capacity theorem, the theoretical throughput capacity of an ideal Additive White Gaussian Noise (AWGN) channel is determined as a function of the channel bandwidth[2] and the SNR.

TABLE II
MaBS, MiBS and MR parameters used in the 3GPP's TR38.901 rural macro LOS propagation model [7], [9].

Parameter	MaBS	MiBS	MR (UE)
Carrier frequency	1900 MHz	30 GHz	-
Bandwidth	10 MHz	800 MHz	-
DL/UL Ratio	10/90	50/50	-
Transmit power	43 dBm	35 dBm	31 dBm
Antenna gain	18 dB	15 dB	0 dB
Antenna height	35 m	10 m	4 m
Noise figure	4 dB	4 dB	6 dB
Foliage loss	11 dB	-	-
Rain/Ice margin	0 dB	3 dB	-

The inputs for the heuristic of Alg. 1 are the rail network, the radio channel model parameters described in Tbl. II and the upper-bound throughput requirements for DRO and PC.

[2]BSPP uses *bandwidth* as the radio channel width in Hz.

In Line 1, the RDN is created using the graph *G(N,E)*, where *N* are the TSs and *E* are the optical links along the rail tracks. The RO owns the optical links parallel to all segments between TSs in the rail network. Lines 2-3 obtain the coverage radius for the BSs using the function *3gpp_propag_model* with the respective parameters depending on the BS type and the throughput requirements. Then, in Lines 5 and 6, for every rail segment *e* the minimum number of MaBS and MiBS are equidistantly placed according to the segment length and the BSs' coverage radius. An equidistant placement is used, as the real rail tracks layout is unknown. Line 8 adds the MaBSs nodes into graph *G*. Lines 9-13 add the MiBSs to graph *G* and associate them to the nearest MaBS, if the MiBSs are within the coverage radius of the MaBS. Line 13 removes already associated MiBSs to avoid associating multiple times the same MiBS. Finally, the RDN graph *G* containing the optical links and the dual-frequency RAN is returned in Line 14.

B. Data Center Placement and Assignment Problem (DCPAP)

DCPAP places the DCs and associates them with the TSs, as represented in Fig. 1 with the same colors. The ILP formulation of DCPAP is presented in Eqs. (1)-(10) and the notation is summarized in Tbl. III. DCPAP works over a graph composed of the RDN and the CN with the potential DCs locations. The RDN containing the optical links and the dual-frequency RAN is obtained from BSPP heuristic in Alg. 1. Nodes common to the RDN and the CN are an interconnection between these networks. DCPAP associates BSs with their nearest TS and the bandwidth[3] demand of a TS is equivalent to the sum of individual throughput requirements of its associated TSs. The goal of the DCPAP objective function in Eq. (3) is to minimize the latency and costs. The costs include fees for using optical links in the RDN and CN, and renting computing capacity in DCs. The latency model considers signal propagation in the air and optic fibers and processing delay in intermediary devices and DCs. The routes between TSs and the potential DCs are pre-calculated using Dijkstra's shortest path algorithm. DCPAP returns an optimal subset *C'* of DCs and the mapping between them and the TSs.

Latency minimization objective: Minimizes the latency between TSs and their assigned DCs.

$$z_d = \sum_{n \in N} \sum_{c \in C} \left(x\left(n,c\right) \cdot d\left(n,c\right) \right) \tag{1}$$

Cost minimization objective: Minimizes the cost of the selected DCs and optical links used in the RDN and CN.

$$z_c = \sum_{c \in C} \left(\delta_c \cdot p_c \right) + \sum_{e \in E} \sum_{n \in N} \sum_{c \in C} \left(y\left(e,n,c\right) \cdot B_n \cdot p_e \right) \tag{2}$$

Bi-objective optimization: Minimizes the weighted sum of the two objectives, with α and β being the associated weights.

$$min \ \left(\alpha \cdot z_d + \beta \cdot z_c \right) \tag{3}$$

DC capacity constraint: The bandwidth assigned to DC *c* must be kept below its capacity: V_c.

$$\sum_{n \in N} \left(x\left(n,c\right) \cdot B_n \right) \leq V_c \ , \ \forall c \in C \tag{4}$$

[3]DCPAP uses *bandwidth* as the throughput capacity in bits per second.

Link capacity constraint: The bandwidth passing through optical link *e* must be kept below its capacity: U_e.

$$\sum_{n \in N} \sum_{c \in C} \left(y\left(e,n,c\right) \cdot B_n \right) \leq U_e, \ \forall e \in E \tag{5}$$

Latency constraint: The latency in the connection between TS *n* and its assigned DC *c* must be below an upper limit: *T*.

$$\sum_{c \in C} \left(x\left(n,c\right) \cdot d\left(n,c\right) \right) \ \leq T, \forall n \in N \tag{6}$$

Single assignment constraint: TS *n* is assigned to exactly one DC *c*.

$$\sum_{c \in C} x\left(n,c\right) = 1, \ \forall n \in N \tag{7}$$

DC number constraint: At most, *K* DCs can be placed in the network.

$$\sum_{c \in C} \delta_c \leq K \tag{8}$$

Active DC constraint: DC *c* processes for TS *n* only if it is active.

$$x\left(n,c\right) \leq \delta_c, \forall n \in N, \forall c \in C \tag{9}$$

Shortest path constraint: If TS *n* is assigned to DC *c*, then the edges in the shortest path from *n* to *c* must be active.

$$y\left(e,n,c\right) = x\left(n,c\right), \forall n \in N, \forall c \in C, \forall e \in S\left(n,c\right) \tag{10}$$

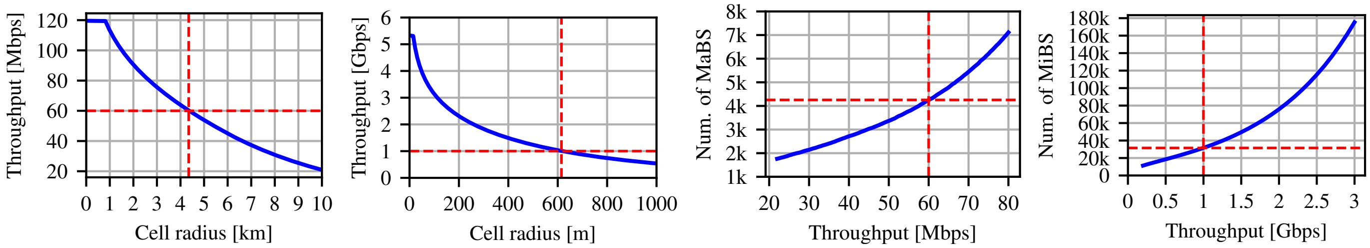
TABLE III
DCPAP MODEL PARAMETERS WITH BANDWIDTH (BW) GIVEN IN MBPS, LATENCY IN MS AND COST IN COST UNIT (CU).

Input parameters	
$N : \{N_1, N_2, ..., N_n\}, n \in \mathbb{Z}^+$	Set of TSs.
$E : \{E_1, E_2, ..., E_m\}, m \in \mathbb{Z}^+$	Set of optical links.
$C : \{C_1, C_2, ..., C_p\}, p \in \mathbb{Z}^+$	Set of potential DCs. $C \subseteq N$
$B : \{B_1, B_2, ..., B_n\}, n \in \mathbb{Z}^+$	Set of TSs' BW demands.
$U_e, \forall e \in E$	BW capacity of optical link *e*.
$V_c, \forall c \in C$	BW capacity of potential DC *c*.
T	Maximum tolerated latency.
K	Maximum number of DCs.
$sp(n,c), \forall n \in N, \forall c \in C$	Delay in shortest path from TS *n* to DC *c*.
$S(n,c), \forall n \in N, \forall c \in C$	Edges in shortest path from TS *n* to DC *c*.
$d(n,c), \forall n \in N, \forall c \in C$	Total latency from TS *n* to DC *c*.
p_e	Cost of edge *e*.
p_c	Cost of DC *c*.
Output parameters	
$x(n,c), n \in N, c \in C$	Binary variable that is 1 if TS *n* is assigned to DC *c*.
$y(e,n,c), e \in E, n \in N, c \in C$	Binary variable that is 1 if link *e* is used to connect TS *n* to DC *c*.
$\delta_c \ , c \in C$	Binary variable that is 1 if DC *c* is selected by at least one TS.
$C' : \{C'_1, C'_2 \dots C'_{K'}\}, K' \leq K$	Set of selected DCs.
K'	Number of DCs used.

IV. EVALUATIONS & RESULTS

A. Base Station Placement

Considering an average train speed of 100 km/h in the German long-distance rail network [10] and a braking distance of 3.4 km [11], a typical MaBS with a coverage radius of 5 km [6] can simultaneously serve four trains. A MiBS



(a) MaBS UL throughput. (b) MiBS DL throughput. (c) Required number of MaBS. (d) Required number of MiBS.

Fig. 2. Figs. 2a and 2b depict the edge throughput concerning the cell's radius for the MaBS and MiBS computed with the 3GPP's propagation model and parameters in Tbl. II. Figs. 2c and 2d display the required number of MaBSs and MiBSs obtained using the BSPP heuristic of Alg. 1 as the cell's edge throughput requirements for the UL of DRO and the DL of PC increase.

with a cell radius comparable to the length of an inter-city train of about 360 m can simultaneously serve one train, as opposing trains shortly interfere due to the high speeds. Following Tbl. I, the most strict throughput requirements per train are the UpLink (UL) of DRO with 15 Mbps and the DownLink (DL) of PC with 1 Gbps. In contrast, the DL of DRO and the UL of PC are less strict. The upper-bound cell's edge throughput requirements for the MaBSs and MiBSs for the maximum number of trains become 60 Mbps in UL and 1 Gbps in DL, respectively. For assuring the upper-bound cell's edge throughput without invalidating the less strict requirements, the DL/UL ratio assignments in Tbl. II were set for the propagation model used in the BSPP. The cell's edge throughput analysis for the less strict requirements is omitted for brevity. Figs. 2a and 2b present the achievable throughput using the propagation model and the parameters in Tbl. II as a function of the cell's radius for the UL of the MaBS and DL of the MiBS. For 60 Mbps in UL, a MaBS can have a maximum cell radius of 4.35 km, whereas for 1 Gbps in DL, a MiBS can have a maximum cell radius of 610 m.

B. Required Number of Base Stations

This evaluation explored the impact of the cells' edge throughput demand on the required number of BSs for the German long-distance rail network. The BSPP heuristic in Alg. 1 was executed by increasing the cell's edge throughput demands for the UL of DRO and DL of PC. Figs. 2c and 2d depict how the number of MaBSs and MiBSs vary in function of the cell's edge throughput demands, respectively. Both graphs follow an exponential behavior in which the number of BSs rapidly grows for larger cell's edge throughput demands. For the previous scenario with a cell's edge throughput demands of 60 Mbps in UL for DRO and 1 Gbps in DL for PC, it was estimated that 4,252 MaBSs and 31,616 MiBSs are needed.

C. Data Center Placement and Assignment

The DCPAP was used to minimize the latency and costs as the number of potential DCs increases and their renting costs are kept low. The RDN was obtained from the previous evaluation. The CN was modeled using the Germany50 topology [12], which has fifty potential DCs locations. The column *Scenario 1* in Tbl. IV summarizes the parameters used for the ILP formulation. *U_RDN*, *p_RDN*, *U_CN* and *p_CN* correspond to the BW capacity and costs of optical links in the RDN and CN. Bandwidth capacities are multiples of commercially available links and costs follow a model per throughput unit. A DC placement and assignment is shown in Fig 4. This map corresponds to *K=8* DCs, where clusters of TSs are formed around the selected DCs locations.

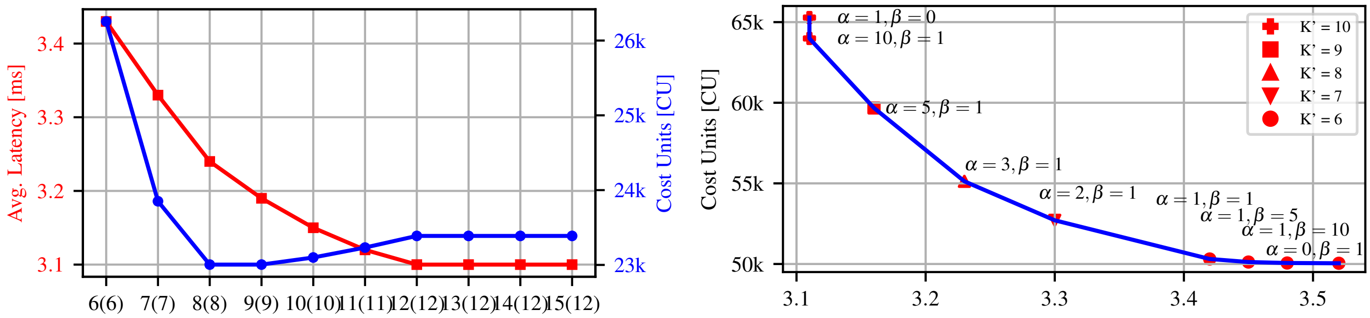
Fig. 3a shows the average latency and the cost as a function of the number of potential DCs *K*. There is a decreasing trend in the latency as the number of DCs *K* increases due to TSs having more DCs nearby. For *K=6* up to *K=12*, the DCPAP places the maximum number of DCs in the network, i.e. *K'=K*. However, after *K=12* placing more DCs does not significantly improve latency. Thus, the DCPAP does not place more DCs, i.e. *K'=12<K*. Regarding the costs, there is a sharp reduction up to *K=8* DCs due to the paths between TSs and DCs becoming shorter. These savings partially cover additional costs for renting processing capacity in more DCs. However, from *K=9* up to *K=12* DCs the savings do not compensate for the extra expenses of new DCs and the cost rises. After *K=12*, the costs remain constant since no new DCs are used.

D. DCPAP Weights Trade-off

This evaluation analyses the impact of the selection for the latency α and cost β weights on the average latency and infrastructure costs. The DCs renting costs are kept high and the used parameters are summarized in column *Scenario 2* of Tbl. IV. Fig 3b shows DCPAP's trade-off between the achieved average latency and the infrastructure costs. Remarkably, for $\beta \geq \alpha$, the number of used DCs *K'* is always 6, which is the minimum number of DCs needed to meet the bandwidth demands of the TSs with the current evaluation parameters.

V. Conclusions

This work presented a two-step approach for planning the network for future railway communications. The Base Station Placement Problem (BSPP) was solved using a heuristic based on a 3GPP's propagation model, which guaranties the necessary throughput at the cell's edge. The Data Center Placement and Assignment Problem (DCPAP) was solved using an Integer Linear Programming (ILP) formulation, which places the data centers and associates these to the train stations while



(a) Average latency and cost as a function of DC number.

(b) DCPAP latency α and cost β weights trade-off.

Fig. 3. Fig. 3a depicts the average latency and cost as the maximum number of DCs K increases according to *Scenario 1* in Tbl. IV. The number of used DCs *K'* is given in parentheses. Fig. 3b shows the trade-off between average latency and cost for the latency α and cost β weights selection of *Scenario 2* in Tbl. IV. The number of used DCs *K'* is denoted by the marker shape.

TABLE IV
PARAMETERS USED FOR THE DCPAP EVALUATION. THE NOTATION IS EXPLAINED IN TABLE III.

Parameter	Scenario 1	Scenario 2
T [ms]	10	10
K	**6,7,8,9,10, 11,12,13,14,15**	10
V_c [Gbps]	200	200
U_{RDN} [Gbps]	40	40
p_{RDN} [CU/(Mbps·m)]	$1 \cdot 10^{-7}$	$1 \cdot 10^{-7}$
U_{CN} [Gbps]	100	100
p_{CN} [CU/(Mbps·m)]	$2 \cdot 10^{-7}$	$2 \cdot 10^{-7}$
p_c [CU]	**1000**	**5000**
(α, β)	(1,1)	**(1,0),(0,1),(1,1),(1,5),(1,10) (2,1),(3,1),(5,1),(10,1)**

minimizing latency and costs. The BSPP and DCPAP were used to evaluate the trade-off between the average latency, the infrastructure cost, the optimal number of data centers and their location. The evaluation was carried out using the German long-distance rail network. The mechanisms provided by this work can help rail operators optimize their network planning tools to meet the future requirements for Digital Rail Operation (DRO) and Passenger Connectivity (PC) services.

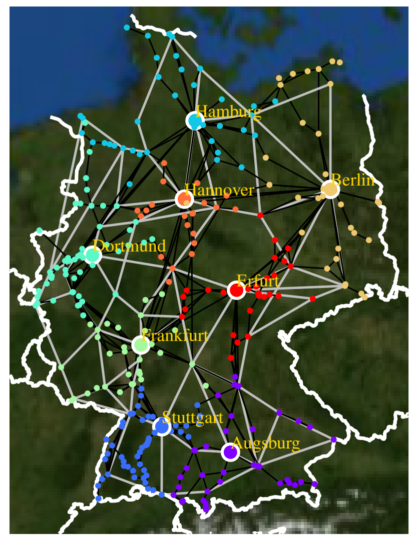


Fig. 4. Placement and assignment map for *K=8* DCs. Large circles and yellow labels with city names mark the location of the selected DCs. TSs are depicted using small dots. Identical colors depict the association between DCs and TSs. The RDN and CN are represented using black and white links, respectively.

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