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Exploring the Insights from Transportation Networks: A Multilayer Network Approach to Distribution Systems Onboard Ships

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Abstract. Creating resilient and multi-layered transportation networks is of paramount importance for modern society, particularly considering the need to respond to a diverse array of risks. These resilient multilayer transport networks appear to share comparable properties with vital multilayer distribution systems found onboard large and complex ships. However, little is currently known regarding the similarities and differences in the design of multilayer networks found in various contexts, such as transportation infrastructure and shipboard distribution systems. This study introduces several multi-modal networks and elucidates their similarities and differences and their design processes. A case study details a typical topology of integrated onboard distribution systems, represented abstractly as a multilayer network to showcase said similarities and differences. The study concludes with the lessons learned from comparing transportation networks with vital onboard distribution systems and provides an outlook for future research into resilient shipboard systems.

Keywords: Onboard distribution systems · Transportation networks · Ship systems' design · Resilience · Transfer of technology

1 Introduction

Network theory can be used to quickly evaluate system performance, system vulnerability or the level of system interconnectedness during the design or operational phase of a system. This 1) allows for a better understanding of the design space because a higher number of options can be calculated [1] and 2) it can prevent mishaps in the system re-design or operation [2]. It is common knowledge amongst ship designers that main and auxiliary systems do not operate in isolation but are, in fact, interrelated and should be designed as such. These relations and interdependencies strengthen further with higher levels of integration. Currently, the level of system integration increases due to higher levels of autonomy required and more complex power, propulsion and energy systems. Multilevel networks, containing multiple types of connections or nodes, form a means to perform system vulnerability analysis of combined systems in early-stage ship design.

Multilayer networks (see [3] for a comprehensive review) have been used in several applications, such as electrical engineering (see land-based power grids in Table 1), architecture, urban engineering and various (public) transport disciplines [4–6]. This study provides a comparison between multilayer network applications in various disciplines, most notably between specific transportation networks and vital onboard distribution systems. The case study focuses on the similarities and differences between a city public transport (PT) network and a topology of integrated onboard distribution systems supporting a single functional end-user. For this study, it was hypothesised that metro networks, due to their comparable size and number of different lines (considered as layers from a multilayer perspective), would prove to be very similar to integrated onboard distribution systems from a network theory perspective and that it would thus be possible

Table 1. Multilayer network applications and their characteristics

Network	Design Freedom	Design Boundary Conditions	Layers
Integrated Onboard Distribution Systems	Full design freedom in ship design phase. Capacity and topology remain constant if design is completed or change at high expenses. Design based on maximum capacity requirements.	Limited volume and weight freedom. Minimal costs.	Cooling water, HVAC, electricity, sensor data, fuel, lubrication oil, etc.
City metro network	Topological architecture remains constant or changes at high expenses over a long time. Capacity can be adjusted, design for mean capacity.	Existing infrastructure, predicted passenger numbers.	Metro lines
PT network	Rail-based transport remains constant. Road-based transport can be dynamically adjusted in route and capacity. Design based on mean capacity.	Existing infrastructure, predicted passenger numbers.	Tram, train, bus
Land-based power grid	Topological architecture and capacity remain constant or change at high expenses	Existing infrastructure, predicted capacity requirements.	High voltage, medium voltage, low voltage

to consider metro network resilience metrics and measures as potential improvements for on-board distribution systems as well.

Integrated Onboard Distribution Systems. Integrated onboard distribution systems are systems consisting of components (machines, equipment, other apparatus) that convert/transform an energy flow (or some other form of generalised flow) and connections/links between them that transport different forms of energy/generalised flow from suppliers to users [7]. Some examples are the cooling water system, HVAC system and the electric power grid. Two of the main challenges in onboard distribution and distributed system design are that 1) the distributed system design from ship type to ship type is vastly different in that it cannot be captured using a small set of parameters describing the spacings and 2) the complexity of distributed systems lies not only in their individual structures but also into the interactions of different systems [8]. Table 1 presents some characteristics of integrated onboard distribution systems and comparable-sized multilayer network applications.

2 Case Study—PT Networks Compared with Integrated Onboard Distribution Systems

This study compares metro networks and integrated onboard distribution systems on some of their key properties: Number of nodes, number of edges and mean degree. Metro networks and, more generally, transport systems, have been studied extensively in previous years [4, 9]. A major focus lies on the resilience of these systems, both in relation to manmade attacks/failures as well as naturally caused failures/disasters. This focus makes transport networks a relevant application to study for the improvement of onboard networks' resilience. Figure 1 shows, for a selection of metro networks [10], the number of stations (nodes), connections (undirected edges), tracks (directed edges) and the mean degree. Note that the number of directed edges (tracks or rails) is exactly twice the number of undirected edges (tunnels or connections between stations).

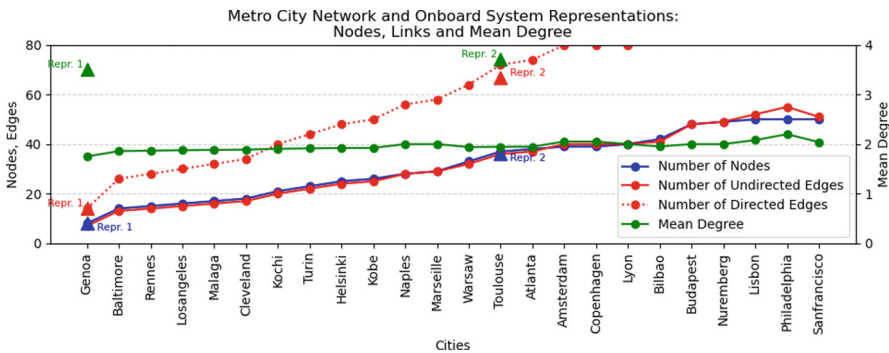


Fig. 1. Metro networks [10] (lines) and onboard system representations (triangle markers) compared on number of nodes, edges and mean degree. The triangles show, in corresponding colors to the lines, the relative location of the onboard system representations

The separate markers (triangles) refer to the case study of integrated onboard distribution systems representations 1 and 2, which are explained in more detail later. The figure shows that the mean degree of the metro networks is close to the lower bound mean degree, which follows an asymptotic increasing line in infinity to 2. Therefore, the structure of the metro networks is either close to a path network or a tree network. It is common for smaller metro networks to have a linear, diametrical, x-shaped or circular network [11, 12], the first three being variants on path or tree graphs.

Comparison in L-space and P-space. A second comparison is based on PT network representations: The L-space (physical infrastructure with edges representing lines) and the P-space (service space; two nodes are linked if they are served by at least one common route [13]). Figure 2 shows two networks with eight nodes: A low-detail representation (representation 1) of integrated onboard distribution systems and the metro network of Genoa in L-space and P-space. Here, the metro network consists of a single line (a single layer), therefore, the P-space is a complete graph.

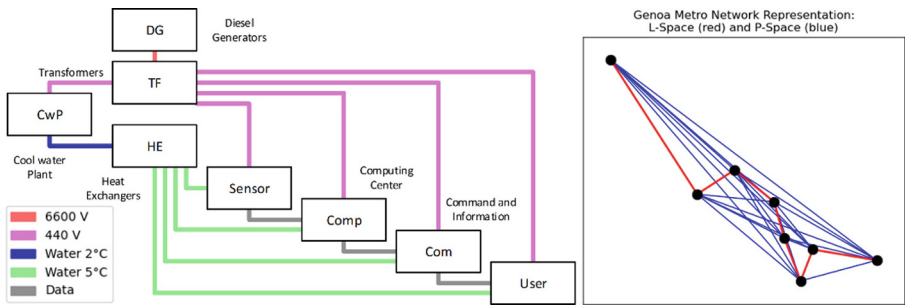


Fig. 2. A network comparison of networks with eight nodes: A) High-level representation of integrated onboard distribution systems and their interrelations. B) The L-space (red) and P-space (blue) metro network representation of Genoa showing stations and physical connections between stations. (Color figure online)

Figure 3 shows the same integrated onboard distribution systems (representation 2) at a higher level of detail and the metro network of Toulouse, which contain respectively 36 and 37 nodes. Since Toulouse contains two metro lines (two layers), the P-space contains two fully connected subgraphs. Whereas the integrated onboard distribution systems contain five layers in both representations, i.e. the “smaller” PT networks contain a lower number of metro lines.

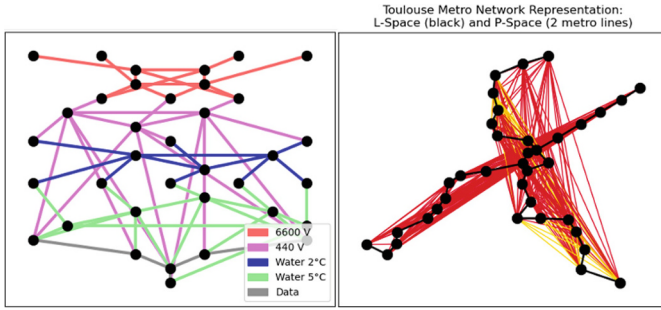


Fig. 3. A network comparison of networks with 36 and 37 nodes: A) More detailed representation of the integrated onboard distribution systems and their interrelations of Fig. 2A [1], B) The L-space (black) and P-space (red, yellow) metro network representation of Toulouse. (Color figure online)

3 Conclusions

Based on the case study, we have drawn the following conclusions regarding the comparison of multilayer network applications.

Sparse networks. Both the integrated onboard distribution systems as well as the metro networks can be considered sparse networks, e.g., they contain significantly less links than the maximum possible number of links. However, due to the inherent property of onboard systems of having supplier nodes and user nodes, this network is closer to a tree-graph, whilst metro networks are closer to path graphs. The tree structure can be found on both the lowest and highest level of detail, however, in-between the supplier and user nodes of each layer we see a more cyclic-based graph between the hub nodes or distribution nodes. The higher mean degree of the onboard networks in comparison to PT networks, as noticeable in Fig. 1, originate from these hub nodes.

Hierarchical reliability. In the early stages of onboard system design, the current focus is on the reliability of separate systems. Future research should take the interaction between these levels regarding the robustness and reliability of the system into account.

Flow layers versus mode layers. When a multilayer network model is used as a tool to understand or improve a system, the definition of the layers is of the utmost importance. We found that there are two main groups within the transport or distribution networks: Heterogenous flow networks and multimodal transportation networks, respectively networks in which the layers represent a different flow, such as a combined cooling water and electricity grid, and networks in which the layers contain the same flow, but the transport or distribution mode depends on the layer. PT networks and cargo transport networks are part of the second group, while power grids and integrated onboard distribution systems are part of the first group. More research is required in determining the differences in reliability and robustness estimations of the different network groups.

Table 2 shows the previously introduced multilayer networks with the characteristics that followed from this study.

Table 2. Multilayer network applications and their characteristics

Network	Type	Interlayer Structure	Intralayer Structure
Integrated Onboard Distribution Systems	Heterogenous Flow Network	Cyclic distribution with tree-like connection to supplier and user nodes	Tree-like
City metro network	Multimodal transportation network	Some shared nodes (hubs), but rarely shared lines and hardly circular structures	Path-like with a rare circle
PT network	Multimodal transportation network	Some shared nodes (hubs), but rarely shared lines and hardly circular structures	Path-like with a rare circle
Land-based power grid	Heterogenous Flow Network	Cyclic distribution with tree-like connection to supplier and user nodes	Tree-like at low voltage levels, circular at high voltage levels

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