Efficient Architecture Evaluation and Generation of Automotive Wiring Harnesses

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***Abstract*—In modern vehicles, the wiring harness connects all components with power and data, and has grown significantly in size, weight, and complexity due to the increasing number of functions. As a response, zonal architectures are emerging as a promising alternative to classical domain-based electrical/electronic (E/E) architectures. Since the architectural decision strongly influences the resulting wiring harness, early evaluation of its impact is crucial. This paper proposes a method to generate zonal architectures by solving a location covering problem and to route both zonal and non-zonal architectures using a multi-commodity flow model. Both problems are formulated as integer linear programs to enable fast and optimal solutions. A final case study demonstrates that increasing the number of zones in zonal architectures reduces wiring length and complexity.**

***Index Terms*—wiring harness, automotive, E/E architecture, zonal architecture, routing, architecture evaluation**

I. Introduction

The wiring harness of a typical compact class vehicle connects several hundred components, spans over a total wire length of more than 1.6 km, and weighs up to 60 kg [1]. This makes it one of the heaviest and most expensive car parts. In the design process, engineers must balance multiple competing objectives, including minimizing wiring length, weight, manufacturing complexity and installation effort, and ensuring compliance with electromagnetic compatibility standards. These objectives are heavily influenced by early-stage architectural decisions, which are difficult and costly to change in later development phases (Fig. 1).

One such key architectural decision is the choice between widespread domain architectures and emerging zonal architectures. A domain architecture allocates electronic control units (ECUs) to components according to their designated functional domain, such as the powertrain or infotainment systems. In contrast, a zonal architecture organizes components into distinct spatial zones, with each zone being managed by a dedicated zone control unit (ZCU) [2]. These ZCUs function as centralized hubs for both power distribution and data communication within their designated zones.

When planning a zonal architecture, it is imperative to determine the number of ZCUs (i.e., the number of zones) and their respective positions. Furthermore, the assignment

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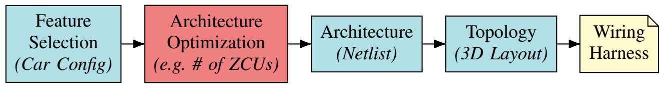

Fig. 1. Overview of the current wiring harness development flow and our proposed addition (red) to optimize its architecture. We generate and evaluate architectural variants and their impact on the resulting wiring harness.

of components to individual zones must be considered. These factors have a substantial impact on the resultant wiring harness, necessitating meticulous evaluation in advance.

This paper proposes two methods that enable efficient generation and evaluation of E/E architectures to support decision making in early design phases. The core idea is to facilitate early-stage assessment through the automated generation of different zonal architectures and the routing of both zonal and non-zonal architectures within a simplified vehicle representation. This allows an estimation of the resulting wiring harness and its characteristics. We present algorithms that enable rapid comparisons of different architectural options. While these algorithms yield optimal solutions for the given input data, their primary purpose is not to produce a fully detailed harness layout. Instead they are designed to work with simplified or even incomplete data, offering early insights into the potential structure and quality of the wiring harness.

The main contributions of our paper are (1) a zonal partitioning algorithm that positions ZCUs and assigns components to them, (2) a routing algorithm that finds an optimal wiring harness for the given architecture, objectives, and constraints, and (3) a case study on zonal architectures.

II. Related Works

Earlier work on optimizing the wiring harness has largely focused on routing optimization, often using heuristic methods such as genetic algorithms [3], [4]. Steiner trees with additional consideration of wire sizing aspects are employed in [5]. A broader overview of routing approaches, including multi-commodity flow formulations, is provided in [6]. Machine learning-based strategies for layout optimization of single wires have been explored in [7]. Wire dimensioning and sizing are addressed in [8] using optimization-based methods. The authors of [9] propose a routing method based on mixed-binary linear programming applied to a fine-grained grid graph, necessitating relaxation techniques.

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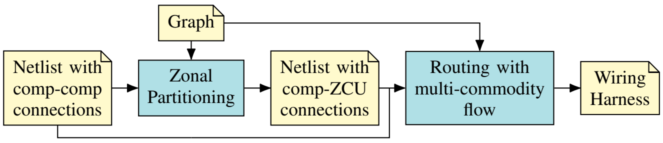


Fig. 2. Overview of our proposed methodology for generating zonal architectures and routing zonal or non-zonal architectures to create wiring harnesses.

Zonal concepts were considered in [10], where the authors examine their use for autonomous vehicles, focusing on data lines and comparing fixed ZCU configurations with domain-based architectures. The creation and evaluation of zonal architectures are addressed in [11], where k-means clustering is used to define zones and Dijkstra's algorithm is applied for routing. Their evaluation focuses on criteria such as complexity, weight, and cost, but without formal optimization models.

While these previous works generate zonal architectures, they lack a fast optimization method that can be used early in the design process to generate optimized zonal and non-zonal wiring harnesses, allowing the efficient evaluation of various architectures. This paper seeks to close this gap.

III. Methodology

A. Problem Formulation

The *zonal partitioning problem* and the *harness routing problem* are based on an undirected graph $G = (V, E)$ with a set of nodes V and a set of edges E. The nodes include all possible locations of components in 3D space, while the edges define the possible paths usable for the wires of the wiring harness. The graph reflects a simplified, application-specific model that captures realistic routing possibilities without introducing unnecessary complexity (see left column in Fig. 3).

Every edge e defines edge costs using the Euclidean distance d_e of the edge and optionally a capacity u_e, that limits the cross-sectional area usable for wires. To simplify algorithms, the graph can be interpreted as a directed graph with nodes V and arcs A, where each undirected edge $\{i, j\}$ is split up into two opposing directed arcs (i, j) and (j, i) that share their capacity ($u_{ij} + u_{ji} = u_e$) and have the same properties as the edge ($d_{ij} = d_{ji} = d_e$).

The netlist N comprises point-to-point-connections, where each net n connects two components, one located at the start node s_n and the other at the target node t_n. The net uses a wire with cross-sectional area a_n.

The *zonal partitioning problem* uses an existing non-zonal netlist to create a zonal architecture by placing p ZCUs at p different graph nodes. Every component gets assigned to a ZCU and every net is split up into two separate nets connecting the components at s_n and t_n to their assigned ZCU. The placement of the ZCUs and the assignment of components to zones should be optimized, e.g., to obtain spatially compact zones.

The objective of the *routing problem* is to route all nets from their respective start node to their target node using the available edges of the graph while obeying the limited capacity of the edges. Optimization target can be the minimization of a weighted sum of multiple parameters, e.g., the total wire length, the total weight, or the metal weight of the wires.

The power supply of the ZCUs and the data connections between them are not considered in this paper. Our proposed methodology is depicted in Fig. 2.

B. Zonal Partitioning Algorithm

Zonal partitioning transforms a non-zonal base architecture into a zonal architecture by structuring it spatially. It generates a netlist where each net connects a component to a designated ZCU and determines the positions of these ZCUs. Our approach places ZCUs closer to components with high wiring demand while ensuring a balanced distribution of load across all ZCUs. This location covering problem is modeled as p-median problem [12] and formulated as integer linear program (ILP):

$$\min \sum_{c \in C} \sum_{z \in Z} w_c \cdot d(c, z) \cdot y_{cz} \tag{1}$$

$$\text{s.t.} \quad \forall c \in C: \quad \sum_{z \in Z} y_{cz} = 1 \tag{2}$$

$$\forall c \in C,\ z \in Z: \quad y_{cz} \leq x_z \tag{3}$$

$$\sum_{z \in Z} x_z = p \tag{4}$$

The wiring demand w_c of node c is defined as the sum of the cross-sectional areas of all wires required by the components placed at the node. Since all components located at the same node are assigned to a common ZCU, their combined demand is considered collectively. The set C includes all nodes where components are located, while set Z defines candidate nodes where ZCUs may be placed, allowing for constraints on potential locations, e.g., to exclude the roof. The binary decision variable y_{cz} is set to 1, if the node $c \in C$ is assigned to a ZCU at node $z \in Z$, and x_z is set to 1 if node $z \in Z$ is selected as a ZCU. The distance $d(c, z)$ represents the length of the shortest path between nodes c and z in the graph.

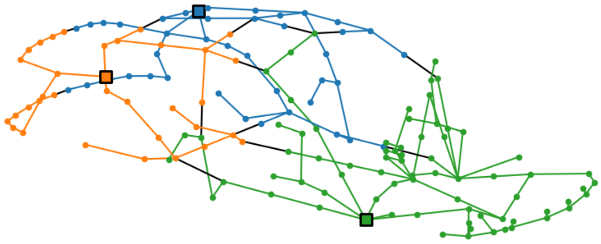
The objective function (1) minimizes the distance from each component to its assigned ZCU, weighted with the cross-sectional areas of the associated wires. This formulation balances the placement of ZCUs near high-demand nodes with an even load distribution across ZCUs.

Constraint (2) guarantees that every component node is assigned to exactly one ZCU; (3) ensures that assignments are only made to nodes where a ZCU is actually placed; and (4) enforces the placement of exactly p ZCUs. The results of the ILP are the locations of the ZCUs and the assignment of each component to exactly one ZCU (see left column in Fig. 3).

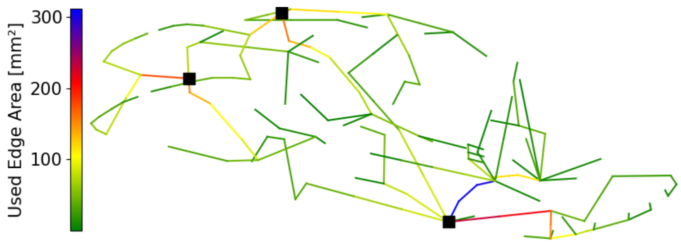
C. Harness Routing Algorithm

The key point of the routing problem is to comply with the limited edge capacities usable for wires while minimizing the total wire length. This is achieved by formulating the routing problem as ILP that combines hard limitations such as the edge capacities as constraints with the minimization of the wiring length as objective function.

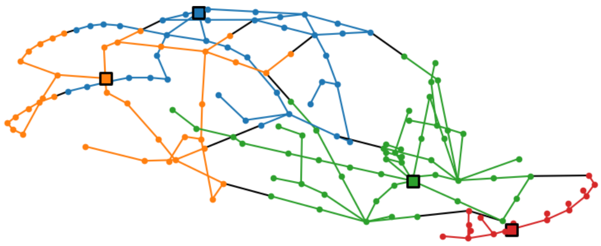
The routing is based on the multi-commodity flow problem whereby nets are interpreted as fluids with a continuous flow



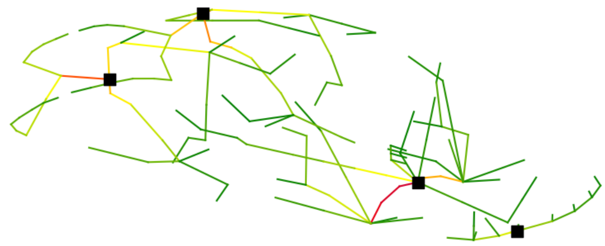
(a) Zonal partitioning with 3 ZCUs.



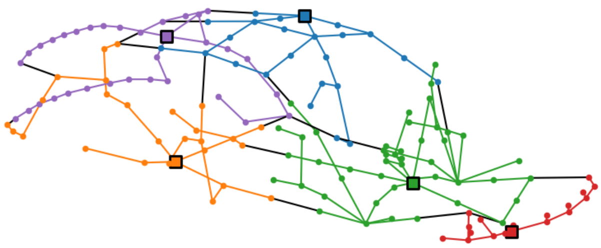
(b) Routed wiring harness with 3 ZCUs.



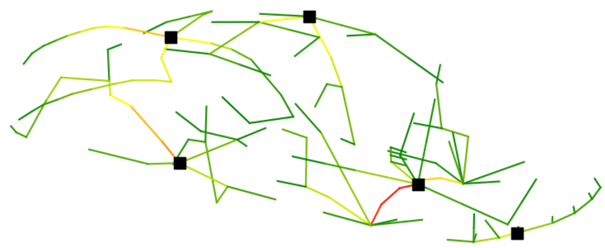
(c) Zonal partitioning with 4 ZCUs; compared to (a), the additional zone comprises the front bumper, the green ZCU has been moved and the assignment to the zones has been swapped for some nodes.



(d) Routed wiring harness with 4 ZCUs; differences to (b) are near the additional ZCU at the front bumper, but also at the roof and floor due to swapped zone assignments of some nodes.



(e) Zonal partitioning with 5 ZCUs; compared to (c) the added zone is at the rear left. The blue and orange ZCU and zones moved.



(f) Routed wiring harness with 5 ZCUs; differences to (d) are at the rear, floor and roof of the vehicle.

Fig. 3. Left column: zonal partitioning of a car. The zones are highlighted in different colors and ZCUs are marked as black-outlined squares. For visualization purposes, edges where both nodes belong to the same zone are colored as belonging to the zone, although the zonal partitioning only classifies nodes. Right column: routed wiring harness for the respective zonal architecture. The color of the edge indicates the cross-sectional area of the edge that is used by wires. The color scale is the same across the figures and edges without wires are not shown. The black squares mark the ZCUs. For p ZCUs there are p unconnected wiring harnesses, one per zone. The car model is positioned with its front bumper pointing towards the right.

along graph edges from source node (flow source) to target node (flow sink). The flow of a net has to remain undivided because the wire represented by the flow is a single physical entity that cannot be split across multiple paths. This is modeled with a binary decision variable f_{ij}^n for each graph arc and net, that is 1 if the wire of the net n is routed along the arc (i, j). The linear program is formulated as:

$$\min \sum_{n \in N} \sum_{(i,j) \in A} d_{ij} \cdot f_{ij}^n \tag{5}$$

$$\text{s.t.} \quad \forall n \in N: \quad \sum_{j:(s_n,j) \in A} f_{s_n j}^n = 1 \tag{6}$$

$$\forall n \in N: \quad \sum_{i:(i,t_n) \in A} f_{i t_n}^n = 1 \tag{7}$$

$$\forall n \in N, \quad \forall v \in V \setminus \{s_n, t_n\}: \quad \sum_{j:(v,j) \in A} f_{vj}^n - \sum_{i:(i,v) \in A} f_{iv}^n = 0 \tag{8}$$

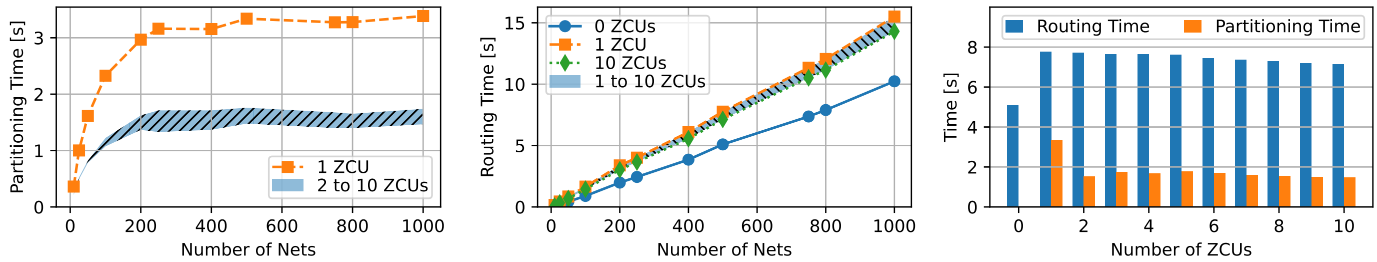
$$\forall \{i,j\} \in E: \quad \sum_{n \in N} a_n \cdot (f_{ij}^n + f_{ji}^n) \le u_{ij} + u_{ji}. \tag{9}$$

The objective function (5) of the ILP minimizes the total length of all wires, defined as the sum of the distances of all arcs used across all nets.

An undivided flow from source to sink is ensured by flow conservation constraints. For every source node of a net, only one unit of flow along a single arc, i.e., only a single wire, can leave the node, as formulated in (6). The analog constraint (7) for sink nodes forces exactly one unit of flow from a single arc to reach the target. For every intermediate node, the total incoming flow must equal the total outgoing flow, to ensure that the flow does not stop amid, as modeled in (8). To simplify the ILP, all variables for flow entering the source and leaving the sink are omitted as they would be zero in any valid solution.

The limited edge capacity is modeled in (9). The cross-sectional areas of all wires traversing an edge are summed, omitting geometric feasibility checks such as circle packing, as the emphasis is on a rough estimate rather than a detailed physical layout.

The result of the algorithm is the path for each net from its respective start node to its end node, which together form



(a) Time needed for creating a zonal architecture with the partitioning algorithm as a function of the number of nets in the input architecture. The runtimes for architectures from 2 to 10 ZCUs are all in the hatched area, but with no consistent order.

(b) Time needed for routing of an architecture as a function of the number of nets in the input architecture. The runtimes for zonal architectures are all in the hatched area, with consistent order: the runtime decreases as the number of ZCU increases.

(c) Routing and partitioning time as a function of the number of ZCUs for an architecture comprising 500 nets.

Fig. 4. Runtime scaling of zonal partitioning and routing algorithms depending on the number of nets in (a) and (b), and the number of ZCUs in (c).

the wiring harness. For a zonal architecture with p zones, the wiring harness consists of p distinct and unconnected partial wiring harnesses, where each one is connected to exactly one ZCU.

The described formulation demonstrates a single objective (total wire length), node-based constraints (flow conservation) and edge-based constraints (edge capacity). The modeling as ILP enables the simple extension to a multi-objective optimization, e.g., by incorporating wire weight or costs. Additional net-based constraints can restrict individual wire lengths, while constraints on multiple nodes and edges can enforce minimum bend radii of wires.

Despite considering an NP-complete multi-commodity flow problem [13], our approach returns *optimal* results within reasonable time for current car architectures (see next section).

IV. Experimental Results

We evaluated the zonal partitioning and routing algorithms presented in the previous section with a comprehensive synthetic data set. All test cases use the same base graph representing the physical topology of the vehicle (see Fig. 3). To define the E/E architecture, each test case uses an individual non-zonal base netlist that is randomly generated and contains only point-to-point connections. The cross-sectional areas assigned to each net are sampled from a distribution derived from real-world automotive data. The wires to connect the ZCUs with each other are not considered, as these are regarded negligible for a small number of zones.

The algorithms have been implemented in Python and executed using an Intel i7-12700K CPU and 32 GB of RAM. Gurobi was utilized as the solver for the ILPs.

The runtime of the zonal partitioning algorithm scales with the number of decision variables of the ILP, i.e., the number of graph nodes at which components are placed and the number of nodes, where ZCUs may be placed. Since the graph and the permitted ZCU positions are fixed in our test cases, only the number of components has an influence. When the number of nets (and thus components) is increased, the runtime initially increases but converges when there are more than 200 nets (see Fig. 4a). As the number of components increases, the additional components are placed at nodes where at least one component is already present (since the number of nodes is limited in the graph). These are combined in the algorithm via the wiring demand w_c and therefore do not create additional decision variables that would increase the runtime.

The routing algorithm scales linearly with the number of nets, requiring approximately 15 seconds to route 1000 nets in a zonal architecture (see Fig. 4b). For a constant number of nets, the routing time decreases slightly as the number of ZCUs increases. This phenomenon can be attributed to the tendency of nets to become shorter due to the closer proximity of ZCUs. Routing a non-zonal architecture takes roughly two thirds of the time required for an equivalent zonal architecture. This difference results from the fact that introducing ZCUs effectively doubles the number of nets. Each original net is divided into two nets, with each component being connected individually to a ZCU.

For an architecture comprising 500 nets, the zonal partitioning takes about 1.5 seconds, while the routing requires approximately 8 seconds (see Fig. 4c). The evaluation of a single base architecture across a range of zero to ten ZCUs requires approximately 100 seconds in total. This short runtime allows for efficient architectural exploration during the early design phases. Since routing uses the results of the zonal partitioning, these steps must be performed sequentially (for the same input data). However, the calculation for different numbers of zones is independent and can be parallelized, which significantly reduces the runtime.

Relevant metrics of the resulting wiring harnesses are total wire length, mean wire length and maximum wire length. As the number of ZCUs increases, the total wire length decreases, as shown in Fig. 5. The wire length is reduced to approximately 42% of the non-zonal architecture's length when ten ZCUs are employed. The previously mentioned doubling of the number of nets in zonal architectures compared to the base architecture is reflected in the total wire length. However, for one ZCU the total length does not double, but only increases to approximately 160%, because the centrally positioned ZCU shortens many individual connections. Using two ZCUs, the total wire length is nearly equal to that of the non-zonal architecture, despite

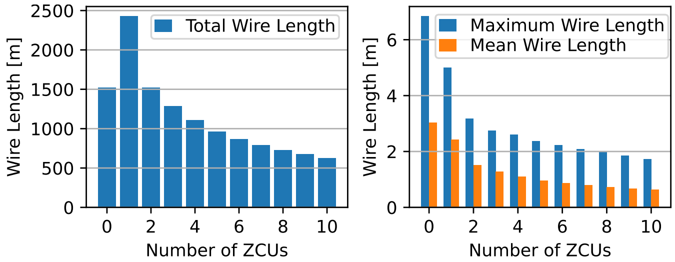


Fig. 5. Total, mean, and maximum wire length of wiring harnesses as a function of the number of ZCUs for an architecture comprising 500 nets. Transitioning from a non-zonal to a zonal architecture (≥ 1 ZCU) doubles the number of nets, as each component is directly connected to a ZCU (creating two nets for a point-to-point connection). This leads to the peak in total wire length for one ZCU.

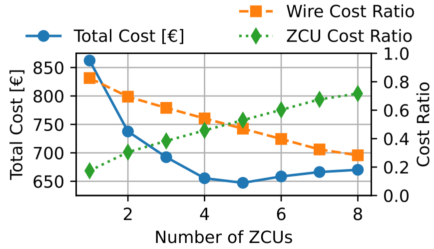


Fig. 6. Cost of zonal architectures as a function of the number of ZCUs. The total cost combines ZCU cost [11] and wire cost (based on copper price) and reaches a minimum at five ZCUs. As the number of ZCUs increases, their share of the total cost rises, while the share of wire cost decreases.

a completely different architecture and wiring harness. From three ZCUs onward, the total wiring length falls below that of the non-zonal architecture and continues to decrease with each additional ZCU.

A decline in mean wire length is observed as the number of ZCUs increases. It falls from the non-zonal architecture to around 50% when two ZCUs are used. Beyond that, it decreases at a slower rate, reaching approximately 21% of the original mean wire length with ten ZCUs. Similarly, the maximum wire length initially drops sharply to about 46% with two ZCUs, then declines more gradually, reaching roughly 27% of the original maximum wire length with ten ZCUs.

These trends highlight the effectiveness of zonal architectures: As the number of ZCUs increases, the total, mean, and maximum wire lengths all decrease. Shorter wiring reduces material and hardware costs, and simplifies installation and automation. However, these benefits come with a trade-off: ZCUs are complex electronic units with their own hardware and software requirements. Using a simplified model, the potential cost savings for zonal architectures can be evaluated. According to [11], the total cost for ZCUs increases with the number of units, even though complexity and cost per unit decrease. At the same time, shorter wire lengths with more ZCUs reduce wiring costs (we use a simplified pricing model based on copper prices). With the data used in our study, the combined costs of wires and ZCUs reaches a minimum at five ZCUs, as shown in Fig. 6. Therefore, using a large number of ZCUs is not desirable, and a balance must be found between wiring efficiency and cost, and ZCU-related complexity and cost.

V. Conclusion

In this paper, we presented a methodology to quickly generate optimized zonal and non-zonal wiring harnesses to enable the efficient evaluation of E/E architectures. Zonal partitioning, i.e., the process of creating a zonal architecture from a non-zonal netlist, is modeled as a p-median problem. The routing step creates the wiring harness based on the architecture and is formulated as a multi-commodity flow problem. Both algorithms are realized as integer linear programs, enabling the fast computation of optimal solutions.

We have shown that optimized zonal architectures lead to a reduction in the total, mean, and maximum wire length of the resulting wiring harness. While the improvements become more significant as the number of ZCUs increases, this is offset by the cost and complexity of the additional ZCUs.

For future work, our ILP-based formulation can be extended to support multi-objective optimization. This will allow the inclusion of additional weighted criteria such as wire weights, bundling density of the harness, or even more complex constraints such as the maximum power or the number of pins of individual ZCUs.

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