Structuring of Methods to Estimate Benefits of Partial Networking

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Abstract: Partial Networking, as a mechanism for moving-to-sleep and waking-up embedded systems, is beneficial for saving energy within a vehicle (or within other complex distributed systems). Even though a number of models exist which identify benefits of partial networking, they often address rather specific cases. Moreover, these fragmented efforts do not necessarily make explicit which methodological steps were taken. Explicating and analysing methodologies of existing research is beneficial to construct an overarching structure how to estimate potential energy savings for partial networking implementations. This structure can be used to select which steps to take to investigate the savings, and how to construct an argument for presenting the findings. This paper describes initial results of such a research. It reviews several models, illuminates their (sometimes not explicitly documented) methods, and outlines a generalized sequence for estimating partial networking benefits. Besides, it provides a list of questions to consider when introducing partial networking. The outlined methods and the analysis can be of interest to other domains interested in energy savings, such as smart grids, smart cities, and internet of things.

1 INTRODUCTION

Saving energy by reducing consumption of in-vehicle components, such as ECUs (Electronic Control Units), is essential for both electric as traditional vehicles. Specifically, switching ECUs from a fully active state to a less power demanding state can provide several advantages (Butzkamm and Bollati, 2012):

- Reducing energy consumption which leads to less CO2 emission (thus, tax advantage) and increased range of electric vehicles;
- Optimizing of operational strategy when the vehicle is at rest can support: new comfort functionalities (e.g., the sun roof control); reduced strain on the battery; longer time periods when the engine can be re-started; less fuel is needed to charge the battery;
- Shorter operating time of embedded systems can lead to reduced lifetime requirements for ECUs.

Partial Networking (PartialNW), as a mechanism to put to sleep and wake up ECUs, can provide significant energy savings. It requires models to track and optimize system-level energy consumptions. Such models can provide inputs for the following considerations (Lingadahalli et al., 2016.):

- Feature deployment to ECUs for optimum power consumption;
- Comparison of various electrical architecture alternatives;
- Power budgeting for features;
- Defining the fuel economy drive cycle impact.

This paper reports intermediate outcomes of research directed at systematizing methodologies and constructing a framework to estimate benefits of partial networking. It aims to provide inputs for designing various PartialNW models best suited at different product development stages, based on the available level of details. New models can be constructed by linking inputs (functions/ECUs) to resulting values (CO_2, energy reduction) through the calculation stage. Some values relevant for models are mentioned next to references to best practices of modelling. To note, these values are referred as they are mentioned in the cited publications and are thus linked to contexts and assumptions of those articles. Nevertheless, they can serves as first order estimates and provide useful insights to the models.

The next sections introduce PartialNW and overview models to estimating its benefits. A generalized sequence of estimating benefits and list some relevant issues is presented afterwards.

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2 BACKGROUND

This section starts with an overview of the structure of power savings related to ECUs, continues by introducing partial networking, and then lists potential ECU candidates for partial networking.

2.1 Power Saving Techniques

In general, techniques to obtain power savings for embedded systems include the following (Heinrich and Prehofer, 2013):

1. Improving consumption of an ECU (i.e. CPU) by dynamic hardware resource management:
   a. Dynamic voltage/frequency scaling;
   b. Reducing quality of service to decrease energy consumption;
   c. Energy-efficient task scheduling;
2. Improving system-wide energy consumption:
   a. Dynamic power management (DPM), which deactivates unused components of a system to save energy;
   b. Dynamic voltage scaling and DPM - considers the energy consumption of peripherals (e.g., memory) within standby and activation/deactivation time of the processor.

Such opportunities benefit from three degenerated states of ECUs (Schmutzler et al., 2010:

1. ECU degradation – decreasing the clock rate or feature set;
2. Stop mode – the microprocessor is in a powered stop mode, while all subsystems except the communication subsystem are deactivated;
3. Sleep mode.

This paper concentrates on the latter state, i.e., sleep mode of ECUs. Specifically, the paper concerns methods of estimating benefits of Partial Networking (PartialNW) in connection to energy savings. Other drivers, such as wiring rationalization, system segmentation, and potential impact on security (e.g., in connection to e.g. the “extended vehicle” concept) are not covered here in detail.

2.2 Introduction to Partial Networking

PartialNW, is a coordinated go-to-sleep and wake-up protocol. As part of a network management middleware it aims to maximize the time ECUs sleep to save energy. Its use can realize an additional number of viable sleep scenarios and thus be beneficial for the current consumption of functions when the vehicle is at rest or moving.

PartialNW is a further step in granularity of selective sleep of ECUs, compared to the bus-wide sleep. This bus-level sleep is directly linked to ECUs located on a specific bus, and thus to reasons why and how the bus was constructed. This can constrain the network architecture, because of a bus (as a sub-network) purpose to: (1) correspond to a functional domain, (2) help to restrict the impact of bus or node malfunctions, and (3) decrease the wire length of individual bus arms. For instance, residential functions can be linked to a specific CAN. PartialNW relaxes assumptions behind such bus composition logics. In PartialNW, nodes form clusters which wake up and respond on demand. If a particular cluster is not requested, its participants can move to sleep. This mechanism allows ECU nodes to enter sleep mode even if the bus is active.

Introduction and elaboration of selective sleep affects network communications and the process of its design due to challenging the following paradigms:

- *Cyclic communication*: network management policies allow nodes to move to sleep and wake up again. Therefore, some nodes do not always participate in communication;
- *Deployment* (Heinrich et al., 2016): In 'Energy-focused allocation', software (SW) components are places to reduce the energy demand of the system. For instance, some SW components can be grouped. Within 'Function based allocation' – contrarywise – suppliers provide hardware (HW) and SW components as an integrated system, which can reduce number of active ECUs needed. Modern SW architectures, such as AUTOSAR, introduce independence of SW components from HW components and help to move from the function-based to energy-focused allocations.

While participating in PartialNW, a microcontroller may switch into an unpowered mode. The sleep to active transition time can be up to 100 ms. Sleep mode switches off the power supply of peripherals and microcontroller. Starting can be compared to a cold boot of an ECU (in comparison, Pretended Networking can bring the ECU into the stop mode, where the current consumption would be higher). After moving from sleep to active, the node has an obsolete representation of the system, which might need to be identified again. Potentially, that status can be stored in a persistent memory, but it may require bigger memories.

In case of Automotive Ethernet, additional wake up specifics relevant to PartialNW apply due to the need to establish communication links. Three wake-up mechanisms can be differentiated as follows (Suermann and Müller, 2014):

- Selective wake-up. For instance, the time taken to establish a link according to the BroadR-Reach specification this can be up to 200 ms. If four consequent links shall be established it might sum up to 800 ms, which is unacceptably long for many in-vehicle functions;
- Global wake-up via a separate wake-up line (therefore, the need for a wake-up line arises);
- Global wake-up via the Ethernet network, when transceivers re-send the wake-up signal. The wake-up message spreads swiftly throughout the network. Unneeded clusters are then switched off again.

PartialNW could employ a local decision unit which analyses bus traffic and decides if a s single node is needed (thus, generate a local wake up event). In addition, other nodes must be informed about ECUs which are about to sleep, because a sleeping ECU could generate errors in other ECUs. Equipped with the state of other ECUs, nodes they can decide whether a signal is missing because the responsible cluster or ECU is sleeping, or if an error occurred.

2.3 Candidates for Partial Networking

To benefit from PartialNW, the distributed system properties should include (Huber, 2010):

1. Functions need to have large execution periods, so ECUs can go to sleep;
2. Functions should be distributed to ECUs adequately (in the view of a distributed vs centralized ECU architecture). In other words, sleep modes cannot be applied, if a single unit performs many essential vehicle functions.

As a result, PartialNW candidates are ECUs that do not require cyclic CAN communications, e.g.:

- parking assistance, lane departure, or other systems to be used at specific speeds;
- door, mirror, roof, and seat control modules;
- some elements from the infotainment segment or special accessories (e. g. trailer control units).

3 OVERVIEW OF MODELS TO ESTIMATE BENEFITS OF PARTIAL NETWORKING

This section overviews state of the art solutions to estimate PartialNW benefits. It explicitly outlines the methods behind such calculations. The section starts with first order estimates, introduces the logic of grouping ECUs based on power consumption, and finally overviews several models.

3.1 First Order Estimations of CO2 and Fuel Savings

To calculate **fuel savings,** one can employ the heuristic that an increase of 100 Watt means that fuel consumption rises by 0.1 litre per 100 km. This in turn leads to an increase in CO2 emissions of 2.5 gram per km (Monetti et al., 2012). Alternatively, energy saved by ECUs can be linked to savings in fuel using caloric value of petrol (Schmutzler et al., 2010):

- Assume a caloric value of 10 kWh per liter of petrol and energy efficiency of a car with a combustion engine as 0.225 (efficiency of engine 0.25 * efficiency of a generator 0.9);
- With 3.84 W*t energy savings of sleeping ECUs, Fuel consumption = 3.84/(0.225*10) = 1.71 ml/h * t;
- Fuel reduction is 0.56ml (With Motor Vehicle Emissions Group A driving cycle t=1180s and 11km);
- Reduction of CO_2 is 0.12 g/km (Assuming burning 1L of petrol to produce 2.33 kg CO2).

Also, PartialNW can be linked to the amount of **money saved by avoiding CO_2 penalties** (Huber, 2010)):

- Energy saved per ECU is found by multiplying differences in current and voltage consumptions.
- Assuming that N network nodes can be put into selective sleep, total energy saved per vehicle can be calculated by multiplying the previous value by this number N;
- Assuming 0.0265 grams of CO_2 emissions per kmW, CO_2 saved per km can be determined;
- The resultant CO_2 savings are multiplied by 95 Euro penalties for exceeded emission (CO_2 per km) to find savings per vehicle;
- Cost reduction per ECU can be found by dividing the savings by N nodes.

NB: the values of 0.0265 grams of CO_2 emissions per kmW and 95 Euro penalties (as intended for the EU starting in 2015) are mentioned in (Huber, 2010) without further details. These values depend on the car model used for calculation and the regulatory context of the car use. While the values can change, the outlined method might still hold.

3.2 Inputs: Classes of ECUs

For modelling purposes, power requirements of ECUs can be grouped into classes. For instance, such classes can be linked to how, e.g., NXP Semiconductors differentiates between several types of applications: advance driver assistance systems, in-vehicle networking, body, chassis, powertrain and safety (NXP, 2018). In another example (Schmutzler et al., 2010), four classes of ECUs are distinguished in connection to average power consumptions, i.e., high-end power train, high-end, mid-end, and low-end (average current consumptions in the mentioned article are 400mA, 70 mA, 20 mA, and n/a).

3.3 Estimations using High Level Scenarios

Scenarios may be uses to determine energy savings (such as driving and hybrid charging). (Schmutzler et al., 2010). The logic behind this method is as follows:

1. The power usage of automotive controllers is assumed to correlate with their feature sets and processing power;
2. Several power classes are distinguished: high-end power train, high-end, mid-end, and low-end based on their consumption (Section 3.2);
3. The supply voltage is used for calculations, as most ECUs use linear regulators. Assumptions are: average supply voltage level (12.6V) and an average 1mA quiescent current per ECU while sleeping;
4. Two scenarios are outlined (driving scenario A and a stationary charging scenario B);
5. By estimating which ECUs can sleep, power categories per scenario are outlined. In scenario A 2 high-end and 13 mid-end ECUs are required only 20% of time.
6. Energy savings are estimated as follows:
   - Energy savings in Scenario A are calculated as (320mA-15 (sleeping ECUs) *1mA) *12.6V * t =3.84W * t;
   - Energy savings in Scenario B are calculated 24.26W * t (with 35 ECU sleeping);
   - Yearly savings=60.64 kWh (charging cycle 10 hours, 250 times a year) = 24.26*10*250.

3.4 Detailing Scenarios as a Set of Functions

To detail a scenario, a sequence of function can be linked to a timeline. For instance, w.r.t. scenario A from the previous subsection (i.e., driving), functions linked to ECUs can be as shown in Table 1 (example from Yi and Jeon, 2015).

Table 1: Sequence of functions within a scenario.

Operating sequence	Operating Detail	Operating ECU	Related ECU(s)
1	Ignition on	All ECUs	All
2	Adjust Seat	ECU 1	2,3,4,
…	…	…	…
10	Operating Rear View Camera	ECU 9	10,11,12
11	Ignition off		-

3.5 Steps to Estimate Impact of Networking Mechanisms on Measured Data

Steps to estimate impact of sleep mechanisms using measured data (e.g., on prototype vehicles) can be structured as implied in (Hong et al., 2016):

1. Select ECUs that can be assessed:
   - Obtain measurement data;
   - Identify if an ECU can sleep (with not too much centralized architecture) or move to stop. Consider whether an ECU does not need to operate permanently (e.g., other ECUs don't rely on the messages) and is not safety-critical, e.g. powertrain.
2. Perform test drives to identify ECUs that don't sleep (in the mentioned paper – Vacuum Pump ECU and Body Control Module ECU (as a combination of two ECUs: 1.with accessories ON and 2.Accessories OFF)):
   - Document behavior at startup;
   - Analyze when and how the ECU starts to work (switch-on requirements);
   - Document applicable scenarios (e.g., 1. Urban Test Drive and 2. Freeway Test Drive). Note relevant events and context (e.g., rain conditions are relevant to wipers; speed can be derived from the driving cycle);
3. Estimate energy savings if the ECU could sleep or move to stand-by in such scenarios.

3.6 Estimations in the Design Process

Different product development stages can provide inputs for estimating PartialNW savings as follows (Heinrich and Prehofer, 2013b):

- At the System requirements stage designers can envision Hardware (number of ECUs, ECU Energy Classes (see Section 3.2) and software (Number of features, feature computation class) elements;
- System Architecture stage adds details on HW (Topology, Network Bandwidth) and SW

(architecture as black box, tasks, task computation efforts);

- System design adds to HW network-specific energy consumption and elaborates, e.g., using function point analysis, SW computation efforts of tasks;
- HW/SW Development elaborates ECU Active and sleep times and Task details.

3.7 Function Deployment

Lingadahalli et al., 2016 outline the following way to detail function deployment and alternatives (using Simulink SimEvents):

- Inputs to the model: (1) Feature activation times (as time_deactivated-time_triggered); (2) Feature-to-ECU deployments (with alternatives), e.g. a feature deployment with participating ECUs; and active and inactive power consumption values (Table 2).
- Output: Power partial NW=sum(consumption of all active ECUs)+sum(consumption of all inactive ECUs)+x (extra power due to NW delays and internal times).

Table 2: Consumptions of ECUs w.r.t. deployments.

ECU	Active State Current	Inactive State Current	CAN Bus	Deploy-ment 1 (All ECUs)	Deploy-ment 2 (alter-native)
ECU1	300 mA	100 uA	Bus1	Active	Active
ECU2	200 mA	50 uA	Bus3	Active	Active
ECU3	500 mA	200 uA	Bus2	Active	Inactive
ECU4	800 mA	100 uA	Bus1	Active	Active
ECU5	50 mA	5 uA	Bus1	Active	Active

As a next step, mapping functional chains (Walla et al., 2012) (which are active in specific conditions) to different ECUs can help to investigate potential power savings in more detail. For instance, if a functional chain is not needed for a vehicle speed greater than 20 km/h, corresponding ECUs can degrade their performance (a technique mentioned in Section 2.1).

3.8 Detailed Communications Model

A detailed model of power savings can consider activation/deactivation of components (including SW components within an ECU) and communication power demands (Heinrich et al., 2016). It can include CAN/Ethernet communications (CAN/Ethernet communication controllers, transceivers, power needed to send a message between networks, time and power for activate/de-activate an ECU and SW components). The corresponding steps could be as follows:

1. Assume power consumptions w.r.t. communications, such as:
   - CAN: data rate 500 Kbit/s. Eight bytes per message are user data and 44 bits are communication overhead;
   - Ethernet: data rate 10 Mbit/s. Maximum 1500 bytes per message are user data and 144 - communication overhead;
   - ECU boot time: 250 ms (100-200 ms to boot, then to receive messages to work with), 2.5 W. To de-activate -2.5W;
   - To activate/deactivate a SW component 5.61mWs (5ms for self-test, load data, 1122 MW power by microcontroller);
   - To transfer a message between NWs: 0.12 mWs, transmission time 0.1s;
   - Energy relevant parameters of the network (including communication controllers and transceivers);
2. Construct dependencies of functional elements per function; account for transferred bytes;
3. Identify components needed for speed ranges;
4. Use a context parameter (speed from the New European Driving Cycle);
5. Consider alternative allocations of [SW component / sensor / actuator] structure. Compare Function-based vs Energy-focused allocations (as mentioned in Section 2.2);
6. Obtain energy demands for: CPU, ECU offset (the energy demand of components such as the power supply unit and the voltage regulator), Sensors/actuators, Communication (Comm. Connections, transfer, listener, energy saving mode), and adaptivity (activation/de-activation of SW components, activation/de-activation of ECUs)).

4 ANALYSIS

The models outlined above work with different (types of) inputs and address specific questions. They can be linked to each other in a generalized sequence of estimating partial networking benefits as follows:

1. **Inputs**: scenarios, functions, details of ECUs (potential function deployments, energy consumption or energy class), communication details (if available); →
2. **Processing** as actions to: Consider (alternative) function deployments to ECUs → Identify ECUs that can be put to sleep (by estimating the amount of sleeping ECUs or identifying

ECUs based on function-to-ECUs mappings] → Identify ECU consumption (measurements or estimations – individually or per ECU class); →

3. **Output** as values of: fuel saved → less CO_2 → money saved by avoiding the CO_2 penalty.

The 'processing' step heavily depends on the adopted function/feature deployment (i.e., mapping) alternatives. As the result of analyzing the literature listed in this publication, the following (exemplary) questions can be considered:

1. Can an ECU avoid sending those cyclic messages that other ECUs rely on?
2. Can an ECU stay free from functions that demand very low-latency replies?
3. Can repetitive tasks (that do not require the processing power and flexibility of a microprocessor) be offloaded? E.g., can an ambient light system driven by Pulse Width Modulation (PWM) run on a dedicated hardware (not on the microcontroller)?
4. Can a mapping improve the response time?
5. If a group of sub-functions within an ECU is not needed, can that ECU reduce its energy consumption (in connection to overall structure of energy savings mentioned in Section 2.1)?
6. Can a specific set of (sub-) functions be linked to an ECU for energy saving:
    - sub-functions not needed at specific conditions (such as parking assist, if the vehicle speed is greater than 20 km/h);
    - a specific mode (e.g., an ECU with comfort functionality within a parked vehicle)?

Some issues mentioned above need to be addressed before adopting PartialNW, e.g.:

- state of ECUs after wake-up might need to be renewed;
- errors shall be envisioned if ECUs don't know whether other ECUs are sleeping or awake;
- potential need for extra Sleep Support that tracks ECUs and supports wake-up/shut-down sequences.
- timing needed (i.e., budgeting) for specific functions, if some ECUs still need to wake up.

Related to the latter, analysing Ethernet wake-up specifics can suggest ways to account for performance and system segmentation based on separating wake-up, go-to-sleep mechanisms, and in-vehicle network segments. Specifically, it includes:

- Step-by-step wakeup. (Time to establish all links shall be compared to the performance needed);
- Need for an extra wire. This measure to partition the system corresponds to a wake-up mechanism that acts in parallel and helps to avoid the delay of the step-by-step wakeup. Such a measure is linked to the wiring rationalization, when a power line or a relay is used to wake up a group of ECUs;
- Global wake-up can complement a selective go-to-sleep mechanism.

Altogether, moving away from the logic of having an ECU per major (group of) functions, which can restrict possibilities of selective sleep, Partial NW can assist in energy savings. This section highlighted several aspects to facilitate (cross-related) use of relevant models, including a generalized sequence of estimating PartialNW benefits, relevant processing-related questions, and emerging budgeting and other related issues.

5 CONCLUSIONS

Considering the potential energy savings that PartialNW can provide, there is a need to understand ways to capitalize on it. Unfortunately, the literature on estimated potential savings sometimes misses the description of the methodology steps, does not explicitly outline the context, nor contain discussions on applicability of such methods. Explicating methods behind calculations and aligning existing them can help to construct a structure for future research on estimating potential energy savings. New methods may address practical questions how to assess specific cases by integrating (parts of) different models and thus the decisions if specific approaches should be adopted. While following the general methodical steps, those new methods could be more detailed and tailored to a specific implementation.

This paper reviewed articles related to partial networking and illuminated their (sometimes not explicitly documented) methods. Equipped with this information, a designer can estimate power savings for their system of interest using these methods and first order values listed in this paper, as well can further study the mentioned literature. A researcher may further investigate the methods and construct new models and methods by tabulating and linked existing approaches.

Within a future research agenda, several aspects missing in the relevant literature can be addressed, such as connections between the context of this research and moving-to-sleep and waking-up mechanisms. The relation to design science could be further strengthened. To provide such a comprehensive view, future research may study the generalizability limits of methods to estimate benefits of selective sleep. It can describe a case on applying generalized sequence of estimating partial networking benefits, including relating it to concerns of stakeholders. Moreover, the links between the in-vehicle partial networking and other energy-conscious domains (and their approaches) can be investigated. On example is the applicability of the methods described in this paper to other systems, such as smart grids or smart cities.

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