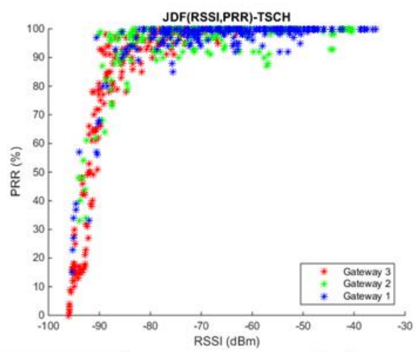
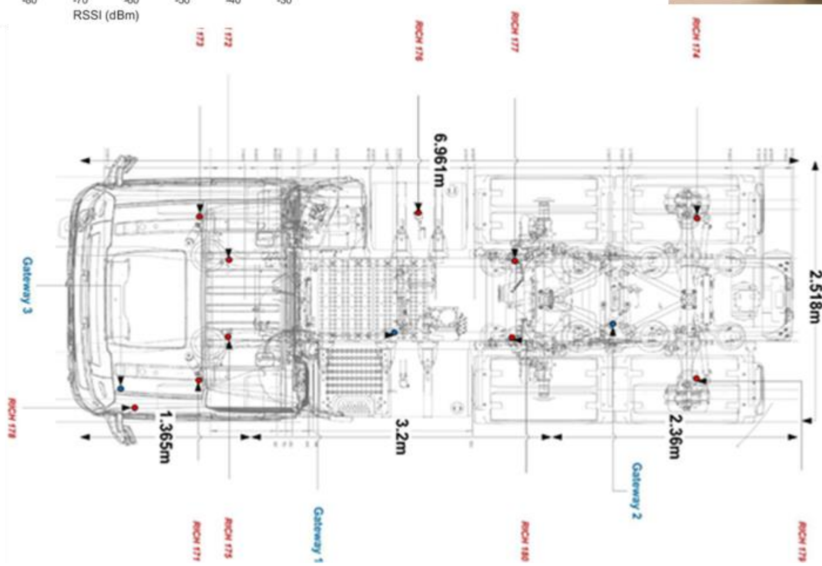
FFI

Wireless Switches and Switch-like Sensors (WISER)





Project within VINNOVA FFI - Fordonsstrategisk Forskning och Innovation

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Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**

For more information: www.vinnova.se/ffi

1. Executive summary

WISER has investigated the applicability of wireless switches for in-vehicle applications. Five promising switch applications have been identified, prototyped, tested and evaluated feasibility of industrialization. Prototypes have been installed in heavy duty trucks and tested under driving conditions. A platform to support short range low rate wireless devices – centered around three network coordinator units - has also been developed. Additionally, engineering practices for the design and development of an in-vehicle short range wireless network has been elucidated. An important component of the network – a suitable communication stack – has also been defined which is built around the IEEE 802.15.4 Low Rate – Wireless Personal Area Network (LR-WPAN) standard and includes a lightweight application protocol. An important technical question – that of providing power autonomy to the wireless switch device – has also been investigated. A major outcome of the project is that while energy harvesting is an interesting power option for a switch device, for a 15-year device lifetime expected in a truck, batteries are a far better and cheaper alternative.

[På Svenska]

WISER har utvärderat lämpligheten att införa trådlösa switchar inom fordon. Fem lovande applikationer har identifierats, prototyper har byggts och implementerats, och en analys på kommersiell lämplighet har utförts. Prototyperna var installerad i lastbilar och var testade i fältet. En plattform har utvecklats som stödjer låg hastighet kommunikation på korta avstånd, baserat på 3 stycken centrala noder. Dessutom har best practice för utveckling av ett fordonsbaserat nätverk tagits fram. En viktig del av nätverket, en lämplig protokollstack, har definierats baserat på IEEEs 802.15.4 korthållsstandard. En annan viktig teknisk fråga, hur man energiförsörjer sådana sensorer, har också utvärderats och en av projektets viktigaste slutsatser är att batterier är lämpligare som lösning båda ur tekniskt och pris perspektiv för att kunna uppnå den förväntade 15-års livslängd i lastbilen.

2. Background

The need for wireless switches/sensors

The use of wireless switches – and more broadly, wireless sensors – in heavy duty vehicles is expected to be beneficial in the following ways:

Reduce part variants – Owing to a significant number of variations in heavy duty truck configurations, many sensors have a disproportionately high number of part variants due to variations in pigtail lengths and encoding of connectors. A wireless sensor would eliminate the pigtail and connector, reducing a multitude of part variants to – in the best case – a single part, which can be installed in all truck variants.

Reduce harness complexity – Packaging of new sensors can involve up-to a few hundred hours of packaging studies, followed by intensive harness development, sourcing and testing. Harnesses are also routed manually in the assembly line – an effort that is time intensive. Harnesses are also prone to wear, resulting in faults that need to be diagnosed and fixed in workshops. The use of wireless sensors reduces the number of cables and has the potential to reduce such adverse impact.

Reduce material cost and impact – Wireless sensors have the potential to reduce the amount of plastic and metal by removing certain harnesses. While the reduction in weight is not likely to be significant, material cost savings – while dependent upon the specific case – can be noteworthy. Plastic and metal used in vehicle wire harnesses also have a significant environmental footprint which wireless sensors can help reduce.

Improve flexibility of new installations – Very often there are calls for new sensors to be installed, but the overhead in packaging harnesses sometimes precludes deployment. Without the need to develop and install wire harnesses, there is also the possibility of reducing development costs and time. In certain locations, it may be very difficult to route harnesses making wireless sensors the only feasible option.

Use of short-range wireless technologies in vehicles – state of practice

The introduction of Tire Pressure Monitoring Systems (TPMS) [1] is in many ways a game changer in the area of in-vehicle wireless sensors. The system has typically been realized by embedding a pressure sensor, either on the rim of the wheel or on wall of the tire (the direct TPMS) which communicates with an Electronic Control Unit (ECU) in the vehicle. The system gathers pressure data from all the wheels in the vehicle and displays the pressure values to the driver, along with a warning if boundary conditions are exceeded. The TPMS is a good example of a feature whose implementation is made easier by the usage of short range wireless communication. Remote controls were among the earliest applications implementing short range wireless technology in vehicles. Wireless key fobs are standard issue for most trucks on the market, while the Volvo FH also includes a wireless Work remote (Figure 1) [2]. In addition, many new proposals are made with regularity, like the use of a short range wireless link for plug-in electric vehicles [3] or alarm systems to prevent theft [4], etc. but they are yet to be inducted into mainstream vehicle electronic systems.

Figure 1 – Tire Pressure Monitoring System (left) and ECS4 Work remote for a Volvo FH (right) which use short-range wireless communication

3. Objective

Having identified legitimate needs for using short range wireless devices for in-vehicle applications, WISER was proposed with the following objectives.

1. Increase the level of competence in developing and deploying in-vehicle short range low rate wireless communication infrastructure.
2. To evaluate a particular class of wireless devices, wireless switches, and determine its technical and commercial feasibility for deployment in heavy duty trucks
3. To evaluate the suitability of energy harvesting as an energy source for wireless switches

4. Project realization

Understanding that goals of the project were along two major themes – infrastructure and applications, an execution plan as shown in Figure 2 was adopted. While detailed information can be found in project reports, a summary of activities and conclusions in each of the main areas of investigation has been provided below.

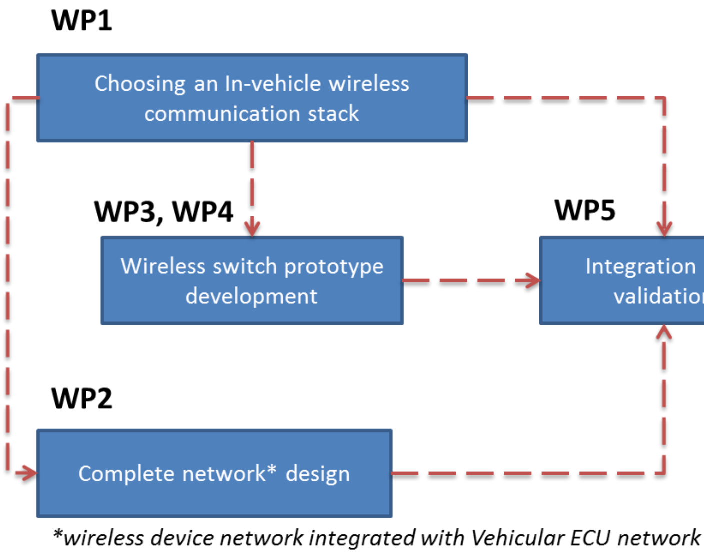

Figure 2 - Project execution plan

Choosing an in-vehicle communication stack

Short range low rate wireless networking has – in the recent past- seen intense activity in both commercial and academic spheres. Protocol design has specifically attracted a lot of attention, prompting us to conduct a systematic survey for options. We found that the market has seen a fair amount of consolidation towards two main stack options – Bluetooth Low Energy and IEEE 802.15.4. Needing the freedom to specify an application interface in a fairly new application area prompted us to gravitate towards IEEE 802.15.4. In addition, having used the 802.15.4 link layer in a few applications in Volvo trucks, this choice allows us to consolidate the platform.

Standard	Theme	Rank
IEEE 802.15.4	This standard offers a general approach to Layer 1/2 WPAN standardization and has found a lot of traction. It has proven to be an effective building block to a wide variety of sensor network solutions.	1
Bluetooth 4.1 LE	This standard is in many ways a commercial 'winner' and has catered to a wide variety of markets. The attempt to be a one-stop solution for a variety of applications is a concern.	2
ITU G.9959	In many ways, a close cousin to IEEE 802.15.4 with a generalist approach, but offering less functionality and used mostly in home automation.	3
DECT-ULE	A traditional voice communication standard being adopted for sensors. The approach is very interesting from a reliability perspective but may be too heavy for a vehicular use case.	3
IEC62591 WirelessHART	These are highly similar industrial sensor network standards which are a definite answer to timing critical	3

IEC62734 ISA100.11a	applications.	
ISO/IEC 14543-3-10:2012	In many ways, an example of the bare minimum that is needed to have an effective WPAN standard. This standard is very innovative in achieving basic functionality with minimum resources.	3
DASH7	An active RFID standard, which is a close cousin to 14543-3-10 in being minimalist.	3

Table 1 - A summary of the survey of short range low rate wireless standards

Another point of interest is the choice of a physical layer which needs to combine propagation characteristics and spectrum licensing. For products with a global footprint, it is necessary to operate in those bands which have worldwide coherence in free licensing – making 2.4 GHz the most attractive option. However, we conducted in sub-GHz ISM and found that from an RF propagation perspective these bands are much more suitable to the in-vehicle environment. The 2.4 GHz band seems the best compromise, but we are better prepared to use sub-GHz bands should opportunities arise.

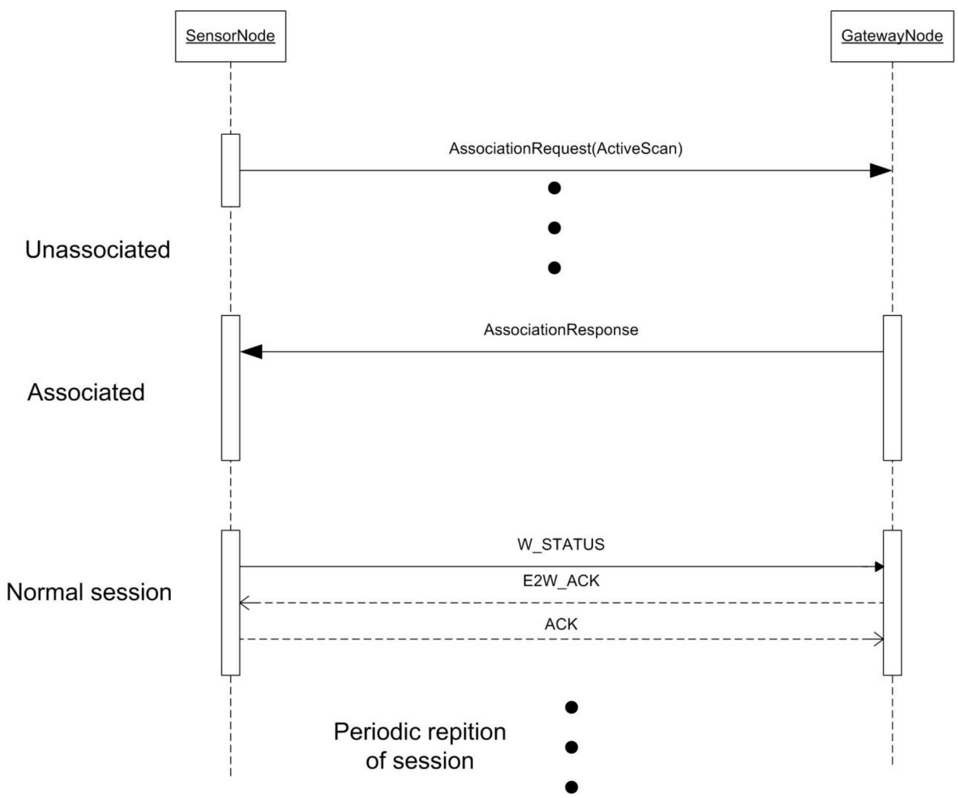

Figure 3 - Application protocol for sensors

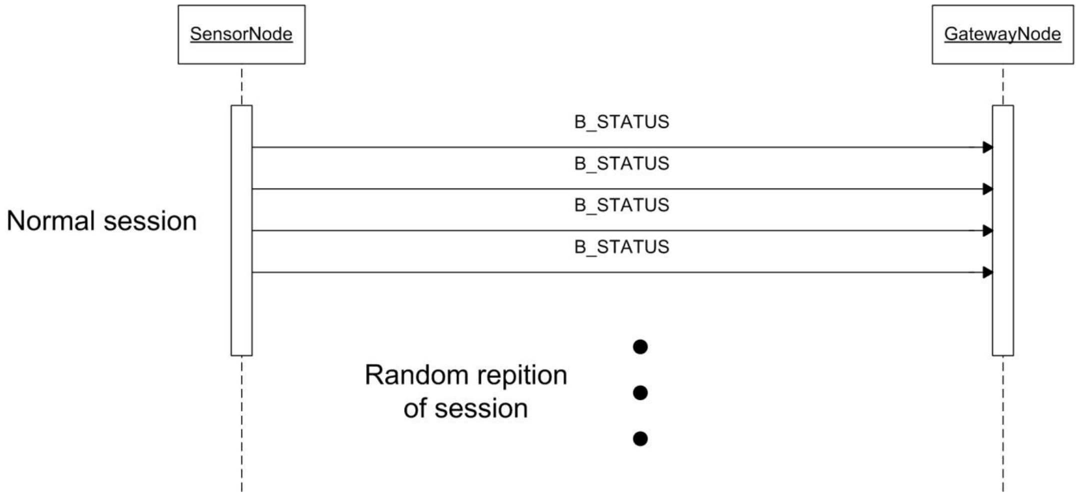

Figure 4 - Application protocol for switches

Attention was then turned to the development of a lightweight application layer protocol that was suitable for wireless sensors and switches. Considering the application needs for in-vehicle sensor/switch applications, the following application protocols (Figure 3 and Figure 4) have been used.

Complete network design

The design of the in-vehicle wireless network first begins with the understanding of the characteristics of such a network, which prompted us to investigate a wide range of possible applications and identifying commonalities and points of difference.

Network characteristic	Determination	Justification
Network hierarchy	Slave-network	An in-vehicle network always exists as an extension of the larger in-vehicle communication network. Keeping in-line with the tradition of having consistent interfaces, the sensor network will be abstracted from the larger network using a gateway.
Network topology	Star/Tree	In the traditional setup of a vehicle control system, a wired sensor is directly connected to a control unit. This setup is expected to be inherited by its wireless counterpart. In certain cases, for the purpose of extending coverage, it is possible that a relay node maybe used. A good example would be connecting a trailer based sensor to the truck. The idea of sensors in a mesh network is not very interesting in an in-vehicle scenario.
Data transfer	1. Sensor initiated periodic 2. Switch initiated random	In a power constrained operational setup, it is essential that most, if not all, communication is sensor initiated. This is meant to reduce the

		duty cycle of the sensor and increase its lifetime. The transfer is periodic in the case of sensors, which are monitoring a parameter, and random in the case of switches, which are monitoring events.
Multiple access	1. CSMA in the case of sensors 2. ALOHA in the case of switches	In the case of sensors periodically transmitting data, it is necessary to reduce the possibility of nodes interfering with each other, requiring the use of a channel access mechanism like CSMA. The use of TDMA has been avoided because of a need to synchronize nodes in the network which requires a penalty to be paid in terms of power consumption. Other multiple access methods like FDMA or CSMA are not traditional in short range wireless networking. Special dispensation is made for switches, where power constraints are even higher and multiple access methods are not used.
Link reliability	Packet reception rates of at least 90%	In the first wave of introduction of wireless sensors and switches, a pragmatic decision has been made to restrict applications to those that are not critical from both timing and safety perspectives. Such applications can tolerate losses of about 1 packet in 10 on average.
Sampling and update rates	In the order of a few seconds	The choice of less critical applications in the first wave of introduction implies that sensors and switches will be sending new data only in the order of once every few seconds or more.

Table 2 - In-vehicle wireless sensor network characteristics

Upon arriving at such a conceptual design, a 'reference' network platform was then installed in a Volvo FH truck to empirically determine finer parameters of the network. The reference network consisted of specially prepared NXP JN5168 [5] nodes programmed with a network testing platform that was specifically developed for this purpose. Experiments conducted using reference network platform helped us gain a good understanding of the statistical properties of the 802.15.4-based 2.4 GHz link.

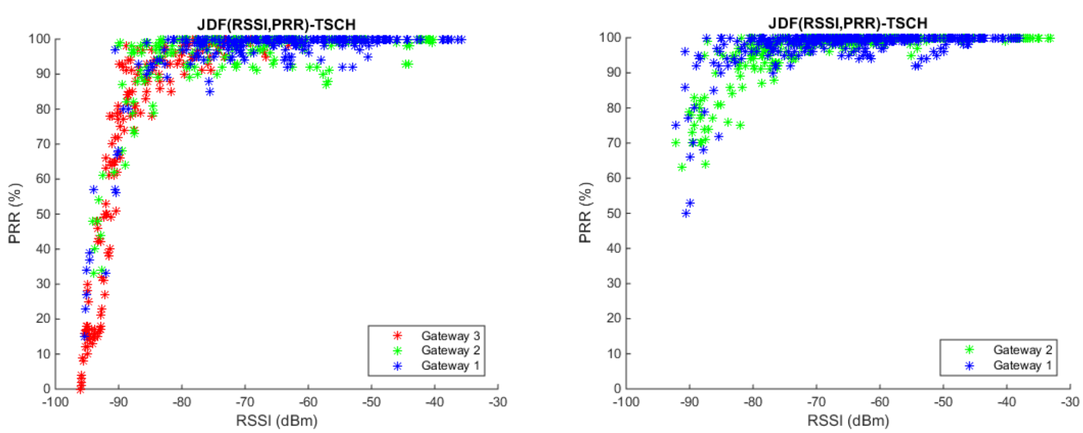

Figure 5 - A joint distribution of packet reception rates and received signal strengths (a) FH 6x2 tractor and (b) FH 6x2 tractor with a semi-trailer

An extensive set of experiments was conducted to evaluate the effects of various parameters on the link, ranging from the time slotting and channel hopping in the MAC layer to the effects of in-band interference from related technologies like 802.11. Our experiments show that it is possible to cover most of the interesting positions for switches and sensors in the chassis of the truck with a network operating at 2.4 GHz, and that several medium-sharing protocols can be implemented to ensure smooth operation both with sensors and switches.

Wireless switch prototype development

The focus on applications began with an extensive survey of switches being used in current vehicles. These applications where put through an evaluation process to select candidates best suited from both technical and commercial perspectives using the following key criteria.

Key criteria	Key concern
Safety	Switches used for safety-critical functions require highly dependable wireless links, but the maturity of dependable low power short range wireless communication remains to be proven for in-vehicle use cases.
Security	Switches used in security-critical functions require highly robust and secure wireless links, but the maturity of secure low power short range wireless communication remains to be proven for in-vehicle use cases.
Timing reliability	Switches usually need be able to fulfill timing requirements both with regards to start-up time, transition time between power states and latency. Strict timing requirements will place high demands on the low power wireless link.
Energy autonomy	For energy autonomous operation, the electrical demands on the wireless switch, particularly power consumption, must be within reasonable limits.
Sampling and update rates	The rate at which the sensor element is sampled and the rate at which sensed information is sent has direct consequences on power consumption and timing criticality.
Operating environment	RF circuitry is liable to be degraded at high operating temperatures and an in-vehicle switch, particularly in the chassis, usually needs to operate in tough mechanical, micro-climatic, and chemical conditions.
Commercial feasibility	The gains in removing harnesses, connectors, overhead, etc. should trump new costs in radio HW, batteries and processes

Table 3- Key criteria for selecting viable wireless switch candidates

Based on the evaluation criteria, the following applications were chosen for prototyping.

Energy harvesting city horn switch - A wireless and self-powered City Horn button (Figure 21) was constructed with a ZF AFIG-0007 energy harvester [6] and a NXP JN5168-001-M03 [7] radio module. Thanks to the spring loaded mechanism in the AFIG-0007 harvester, the button integrated in the steering wheel provides a clear tactile feedback of operation.

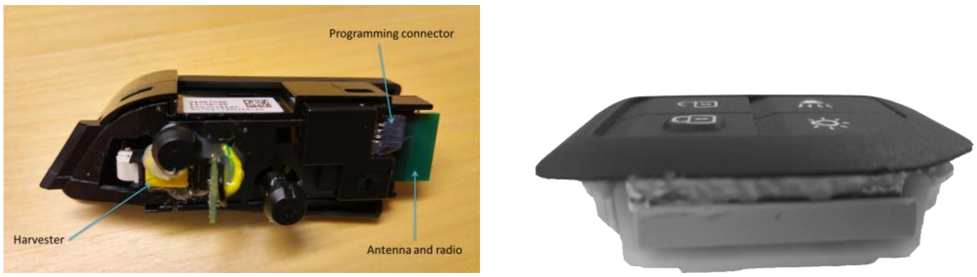

Figure 6 - Prototype energy harvesting city horn switch (left) and energy harvesting keyfob (right)

Energy harvesting keyfob - The prototype is based on the Enocean switch [8], the travel of the stock button of the key fob was deemed too short, and this can be solved with mechanical gearing. Instead of making the button travel longer or redesigning the gearing we made custom hinges so the top of the top of the key fob could tilt either left or right thus extending the actual button travel. The corresponding button would be pressed down as the key fob top tilted and activated the energy harvester.

Figure 7 - Prototype battery powered cab-tilt lock switch (left) and air-filter pressure switch (right)

Battery powered cab-tilt lock switch - The cab lock switch is used to detect if the mechanical cab tilt lock is properly locked and secured. If the lock that keeps the cab from tilting is not properly closed this might become a hazard when driving. A wireless cab tilt lock switch was developed by modifying the current wired switch. The connector of the wired switch was replaced with a NXP JN5168-001-M00 module [7] and a coin cell battery.

Battery powered air-filter pressure switch - The air filter pressure switch is a device that checks if the air filter is clogged, this is done by checking for negative differential pressure in the piping after the air filter compared to the surrounding air. The battery based wireless solution was with a CR 2032 battery for power.

Battery powered trailer door lock switch - The wireless switch concept was extended to the trailer. The trailer door lock switch is made similar to the cab tilt lock switch, with a reed switch sensing the proximity of a magnet. The reed switch is integrated with the transceiver and battery in a molded plastic box. This box was mounted on one door and the magnet on the other and thus sensing if the doors are closed or opened.

Figure 8 - Trailer door lock switch

In addition to developing the individual switch prototypes, it was also essential to develop the necessary gateway/receiver modules. For all tractor based switches a gateway module – based on Volvo ATR's FlexECU platform - that bridges between CAN and 802.15.4 networks was developed.

In-vehicle validation

The prototype switches and gateway so developed were then installed in a test truck for validation using drive tests. The validation platform combining tractor and trailer based devices took the following form. Multiple drive tests using our reference and prototype network test platforms helped us to both understand and tweak network properties.

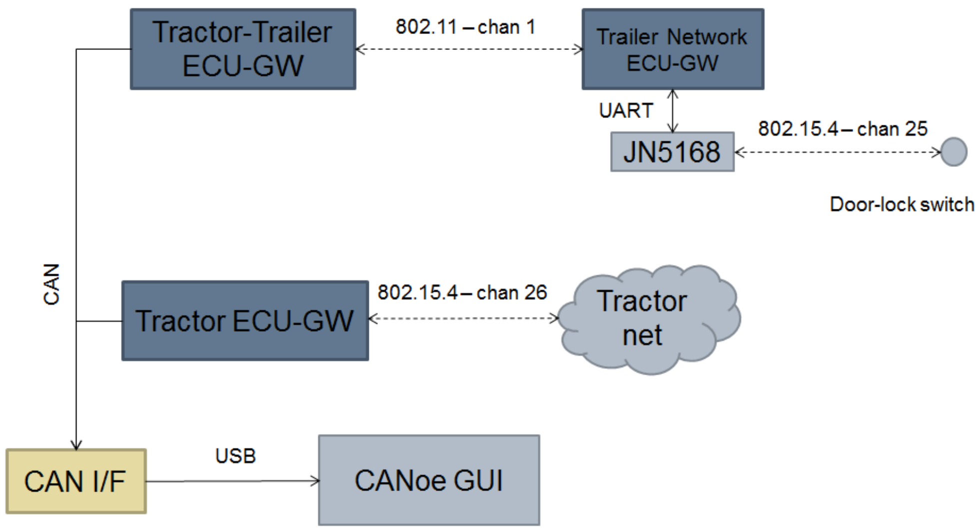

Figure 9 - In-vehicle validation setup

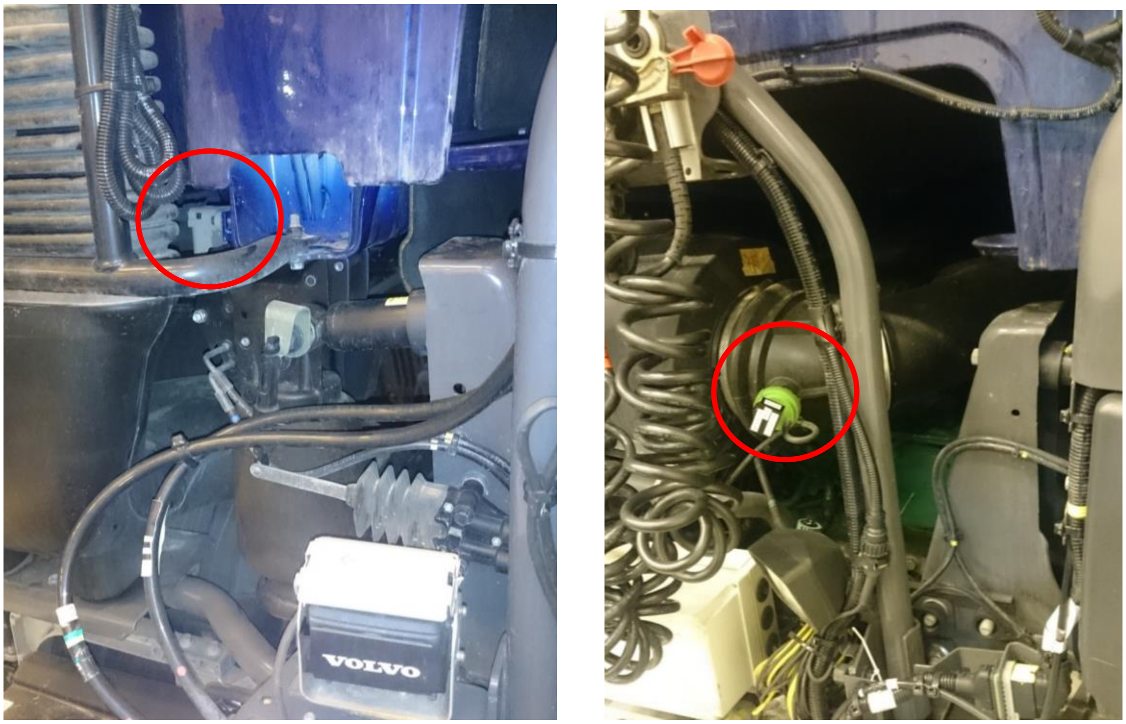

Figure 10 - Installation of cab-tilt lock (left) and air-filter pressure (right) switches

Figure 11 - Installation of trailer door lock switch

5. Results and deliverables

Investigations conducted in WISER has resulted in a significant rise in the maturity of related technologies, as rated by Volvo's technology development process. Specifically project goals have been achieved in the following manner.

Project goal	Fulfilment
Increase the level of competence in developing and deploying in-vehicle short range low rate wireless communication infrastructure	Investigations and experiments conducted in WISER has led to the design of a robust in-vehicle short range wireless network for a select class of non-timing and non-safety critical applications. The design is a combination of concepts and prototypes and has been validated under a variety of driving scenarios
To evaluate a particular class of wireless devices, wireless switches, and determine its technical and commercial feasibility for deployment in heavy duty trucks	Following a systematic survey of possible switch applications, a number of feasible candidates have been chosen and their wireless counterparts have been implemented and validated under driving conditions.
To evaluate the suitability of energy harvesting as an energy source for wireless switches	Having developed battery powered and energy harvesting wireless switch prototypes in WISER, we conclude that for lifetimes of 10-15 years specified for heavy duty truck components, for duty cycle levels specified for wireless switches, batteries are the most competitive choice. The current low level of maturity of energy harvesting technology and the less numerous supplier base for commercial energy harvesting devices means that the situation is likely to remain unchanged for the next few years.

5.1 Delivery to FFI-goals

Target (Swedish text is taken from the programme description)	**Level** (Low, Medium, High)
Specific for FFI Fordonsutveckling	
Utveckla framtida innovativa effektiva och säkra fordonskoncept och/eller delsystem inklusive komponenter *Develop future, innovative, effective, and safe vehicle concepts and/or subsystems including components*	High
Fordonselektroniken möjliggör ”Green, Safe & Connected” *Automotive electronics makes it possible ”Green, Safe & Connected”*	High

Tekniken överförs snabbt till nytta för användaren. Genom robusta, flexibla, kostnads- och vikteffektiva arkitekturer, system och mjukvara *Technology is transferred quickly for the benefit of users. Through robust, flexible, cost- and weight-efficient architectures, systems, and software*	High
Ny materialteknik som möter marknadens långsiktiga krav med speciellt fokus på fordonsstruktur och krävande miljöer *New material technology that fulfills the market's long-term requirements with special focus on vehicle structure and demanding environments*	Low
Utveckla och tillämpa metoder som avsevärt effektiviserar produktutvecklingsprocessen med ökad kvalitet i hela utvecklingskedjan *Develop and apply methods that make product development processes significantly more efficient with increased quality in the whole development cycle*	Medium
Overall for FFI, in the theme areas Climate & Environment and Safety	
Genom ökad forsknings- och innovationskapacitet i Sverige säkra fordonsindustriell konkurrenskraft och arbetstillfällen på lång sikt och helst även på kort sikt *Through increased research and innovation capacity in Sweden secure competitiveness and jobs in the automotive industry in the long term and preferably also in the short term*	High
Utveckla internationellt uppkopplade och konkurrenskraftiga forsknings- och innovationsmiljöer, i vilka bland andra akademi, institut och industri samverkar *Develop internationally connected and competitive research and innovation environments, in which among others academia, institutes and industry collaborate*	Medium
Främja internationell forsknings och innovationsverksamhet där förutsättningar för medverkan i EU:s ramprogram och annan internationell forsknings- och innovationssamverkan noga värderas *Facilitate international research and innovation collaboration where prerequisites for participation in the framework programmes of the EU and other international research and innovation collaboration is scrutinized*	Medium

6. Dissemination and publications

6.1 Knowledge and results dissemination

We have mainly relied on our deliverables to communicate major findings and conclusions derived from the project. This has been complemented by extensive contact with potential suppliers within the industry because we now deem this technology mature enough to proceed to industrialization phases.

7. Conclusions and future research

Short range low rate wireless communication is a promising wire-replacement technology for non-timing-critical and non-safety-critical wireless switches and sensors in vehicles. The work performed in WISER has demonstrated technology platforms and applications to support this conclusion. This technology is therefore at a level of maturity that can support industrialization use cases. The process of industrialization, with associated contact and interaction between industry stakeholders is likely to solve finer engineering details like application standardization. For the class of applications targeted in this project, we find that batteries are more competitive both technically and commercially in comparison with energy harvesting. The complexity, relative lack of maturity and therefore higher cost of energy harvesters is unlikely to pay off for 10-15 year component lifetimes that are specified in the commercial vehicle industry. Perhaps renewed research is necessary to bridge this gap.

Having conducted two research projects WISCON and WISER, the former with university partners, Volvo judges that industrialization must take priority over technology research in the area of wireless sensors/switches and energy harvesting.

However, Volvo has identified credible technology and interoperability gaps in the area of truck-trailer communication in which higher rate wireless links could play a crucial role. This is an area that will be pursued for further research.

8. Participating parties and contact person

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