Position Detection in linear, proximity coupling Networks

Derk Wesemann[1], Stefan Witte[1], and Jan-Stefan Michels[2]

[1]inIT - Institute Industrial IT, OWL University of Applied Sciences, D-32657 Lemgo, Germany
derk.wesemann@hs-owl.de, stefan.witte@hs-owl.de
[2]Weidmüller Interface GmbH & Co. KG, D-32758 Detmold, Germany
janstefan.michels@weidmueller.de

Abstract

This paper describes a method for automatically obtaining the order and position of contactless connected network participants in a linear physical topology. While the sequence of network devices can be determined with quite simple methods in networks with physical interconnections, these methods can not be applied in contactless networks. This work is based on a linear network topology using a backbone rail, which includes mechanisms for contactless energy and data transmission. The position estimation for each attached network device can be performed by determining a specific physical characteristic, which is altered along the rail extension. The proposed solution uses a capacitive resonant circuit to achieve a position detection.

1. Introduction

In any linear shaped network, having knowledge about the sequence of all participants is an important basic precondition for enabling an automated configuration process. If it is possible to quantify a node's position, this information can be used to derive a node's address for instance, but it can also be used for failure detection within a network. This work presents a solution for gathering position information about each node in a contactless network. The precondition is a linear network topology, like it is shown in figure no. 1.

A linear back end provides energy and data connection to the network participants, thus allowing free placement along the mounting rail and encapsulation of nodes. Note that the methods how this connection and supply can be achieved are not within the scope of this paper. The coupling distance between the rail and the nodes is within the range of some millimeters. A first approach for deriving topology information is the determination of the participant sequence, more sophisticated methods will also be able to directly estimate the position of each node.

1.1. Wire-based and wireless analogies

In wire-based networks, position information can be obtained by a special port switching mechanism, i.e. a daisy-chain principle. Each node is equipped with a primary (in) and a secondary (out) port, creating interconnections only between these two kinds of ports. The secondary port is only opened after the primary port is triggered, this way the sequence of all network participants can be determined step-wise. What can not be determined is the network node's physical position. From the point of view of network stability, the daisy chain principle suffers from having a single node failure disabling the entire network, in worst case. Another way of determining the node positions is to capture and analyze the delay times of the signal propagation. This method is applicable in case of long transmission distances, where the time delay is measurably large.

In wireless networks, position estimation can be performed based upon the signal strength indication function (RSSI) [1], which is implemented in most commercial wireless products. Current research focuses on using this signal strength information for generating position awareness inside buildings, for instance, where a GPS signal is not available. The accuracy of this method is limited by the resolution of the RSSI variable, but also by ambient parameters, additional damping effects, the operating frequency, etc. Furthermore, this method needs a running data transmission to retrieve the RSSI value, and can only describe the physical network layout in means of relative parameters, namely the distance between nodes.

2. Problem description

For network administration and configuration demands, having knowledge about the physical network layout is essential information. This information can be used not only for maintenance purposes (i.e. quickly retrieving a specific node), but also for automatically deriving an address scheme.

For the contactless network that is the basis for this work, neither of the existing methods in wired or wireless networks are suitable. A line termination, like it can be used in wired networks at a distinct point is impossible, as there is no galvanic connection between the network medium and the participants. A daisy chain or line termination principle can not be applied. A signal strength indication, like it is used in wireless networks would be basically possible, but the needed resolution is beyond what can be achieved with price-sensitive solutions. The damping factor along the rail is much less compared to a conventional wireless system, and the position difference between two network nodes lies within some centimeters, so the difference in signal strength between two adjacent nodes is extremely small. Capacitive methods like they are used in linear position detection systems, e.g. sliding calipers are widely known and show decent accuracy [2], but their incremental working principle is not applicable to the situation of having several pickup modules being added, removed and interchanged, as they can not determine absolute positions, but relative positions only. The same applies for inductive sensors, which are frequently used for linear positioning devices in production machines. One approach using an array of coils for position detection of a resonant secondary side [3] has been considered to be too complicated for this application.

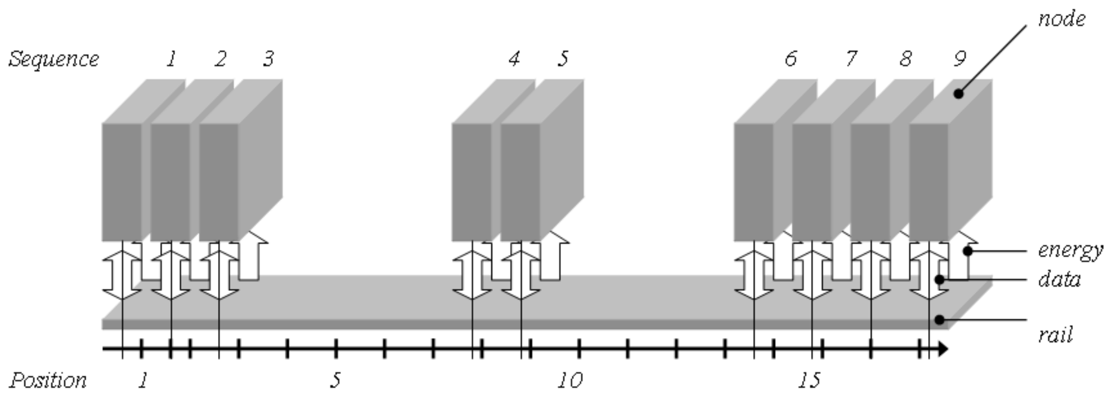

Fig. 1. System description

3. Proposed Solution

For obtaining a sequence order, it is either necessary to count through all network nodes linearly or to be aware of their spatial position. By measuring one physical characteristic that is altered along the rail dimension, a node can determine its position by evaluating this physical property and relating it to the value of the other network members. The available choices for the physical characteristic are limited by the precondition of a contactless network, which makes a resistive method impossible, for instance. An optical method would be basically possible, but it is prone to dust and dirt, which makes it a suboptimal choice for industrial needs. This work proposes an approach based on capacitive coupling. The mounting rail is equipped with an additional inlay, carrying two stripe conductors of variable width. Together with matching electrodes on the secondary side modules, two capacitances are formed, which allow the transmission of two electrical potentials, thus creating a voltage signal and current on the secondary side. The geometrical layout is described by the following illustration:

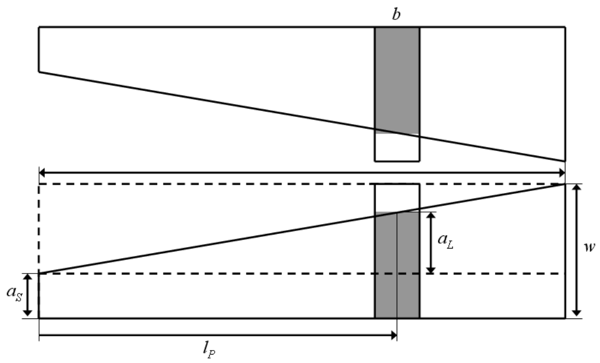

Fig. 2. Geometrical line layout

This triangular layout provides a position dependent coupling capacitance, which can be calculated in the following, general way, with ε_R being the dielectric material constant and d the distance between the electrodes:

$$C_K = \varepsilon_0 \cdot \varepsilon_R \cdot \frac{A}{d} \qquad (1)$$

The effective area A is given by the product of the center height a and the horizontal dimension b of the secondary side electrodes. Depending on the position l of a node, the center height a can be expressed as:

$$a = a_S + a_L \text{, with}$$

$$a_L = \frac{w - a_S}{l} \cdot l_P \quad \Rightarrow \quad a = a_S + \frac{w - a_S}{l} \cdot l_P \qquad (2)$$

The area is depending linearly on the node's position:

$$A = a \cdot b = \left(a_S + \frac{w - a_S}{l} \cdot l_P \right) \cdot b \qquad (3)$$

So the position dependent coupling capacitance can be described by:

$$C_K(l_P) = \varepsilon_0 \cdot \varepsilon_r \cdot \left(a_S + \frac{w - a_S}{l} \cdot l_P \right) \cdot \frac{b}{d} \qquad (4)$$

3.1. Voltage measurement on secondary side

The easiest way of estimating the position in this capacitive arrangement is by measuring the voltage drop on the secondary side. With increasing coupling capacitance, the voltage drop across the coupler decreases, leading to a higher voltage value at the load resistance.

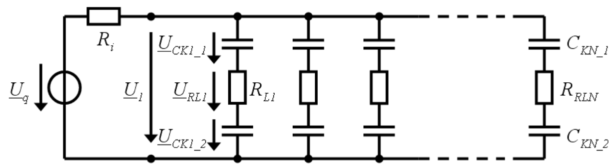

Fig. 3. Circuit variant 1

With an appropriate choice of the load resistance and the operating frequency, the voltage difference between two adjacent positions can be maximized, easing the position detection and differentiability. The circuitry with both coupling capacitors can be regarded as a high-pass filter. With an appropriate choice of the load resistance R_{LN}, the cutoff frequency of the filter can be adjusted to allow a reasonable small operating frequency.

3.2. Serial resonance on secondary side

Having a capacitance in the first place, adding an inductance to create and evaluate a distinct resonant behavior is only a short step away. The inductance which is necessary to create a resonant system might be placed on the secondary side, forming a serial resonance together with the coupling capacitances. An illustration of this setup is shown in figure no. 4:

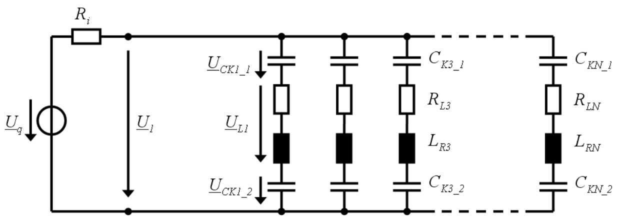

Fig. 4. Circuit variant 2

Compared to the before proposed circuitry, the number of components increases. Additionally, it is not the voltage drop across the secondary side load ($\underline{U}_{L1}$) which entirely defines its position, but the individual resonant frequency itself. From the primary side, not one system resonant frequency f_R can be observed, but several distinct frequency dependent voltage minima (or equivalent current maxima) for each attached node. This way, a node can retrieve its own position by determining its singular resonant frequency, but also can a network master identify the number and position of attached nodes by evaluating the spectrum on the primary side. For retrieving a certain resonant frequency, it is necessary to generate a detectable signal at the secondary side loads (R_L). The voltage drop across the load resistance can be described as:

$$\underline{U}_{RLN} = \frac{R_{LN}}{\frac{2}{j\omega \cdot C_{KN}} + j\omega \cdot L_{RN} + R_{LN}} \cdot \underline{U}_1 \quad (5)$$

The resonant frequency difference between two nodes with the spatial position distance l_D can be expressed by:

$$\Delta f_R = \frac{1}{2\pi \cdot \sqrt{L_R}} \cdot \left| \frac{1}{\sqrt{C}} - \frac{1}{\sqrt{C + \Delta C_K}} \right| \quad (6)$$

with the capacitance difference ΔC_K defined as:

$$\Delta C_K = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{b \cdot (w - a_S) \cdot l_D}{l \cdot d} \quad (7)$$

A simulation of this circuitry shows the following results:

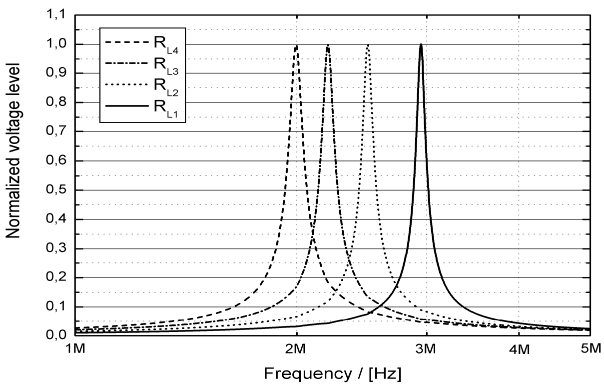

Fig. 5. Circuit variant 2, simulation results

With increasing coupling capacitance C_{KN}, the resonant frequency f_R decreases. This dependency is not linearly, but shows a *1/x*-function.

3.3. System boundaries

The maximum number of nodes that can be detected is limited by the realizable frequency span, resolution and the resonant circuit bandwidth. While the frequency span is a question of device parameters, the minimum frequency deviation is related to the coupling capacitance, and therefore determined by the geometrical layout of the rail. Based on (7), the minimum capacitance difference between two adjacent nodes can be defined as:

$$\Delta C_K = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{b^2 \cdot (w - a_S)}{l \cdot d} \quad (8)$$

One can see that the capacitance difference is inversely proportional to the rail length l and exponentially depending of the module extension b.

4. Practical validation

The theoretical calculations need to be validated with a practical example. Due to manufacturing limitations, a short transmission line design of 25 cm length has been fabricated, carrying two line layouts which vary their width from 2 to 11 mm. Both lines are arranged as described in figure no. 2, allowing different coupling capacitances along the longitudinal extension. On the secondary side, a printed circuit board was used which contains two rectangular electrodes, each 20 x 11 mm² in size. Primary and secondary side boards are separated with a 0.1 mm thick foil of polyethylene (PE) as the dielectric medium, assuring a constant distance between the coupling electrodes.

Table 1. Setup parameters

length *l*	250 mm
width *w*	11 mm
socket height a_S	2 mm
module length *b*	20 mm
dielectric material constant (PE)	2.4
electrode distance *d*	0.1 mm
Electrode area A	76 - 205.6 mm²
coupling capacitance C_K	16.14 - 43.67 pF
probe input resistance	1MΩ
probe input capacitance	47pF
resonant inductance L_R	100 µH

4.1. Voltage reference

In a first attempt, the secondary side voltage based solution was to be validated. Based upon the simulation of the system (including the input impedance of the measurement device), the voltages were measured for different frequencies, which have shown to cover a wide amplitude level.

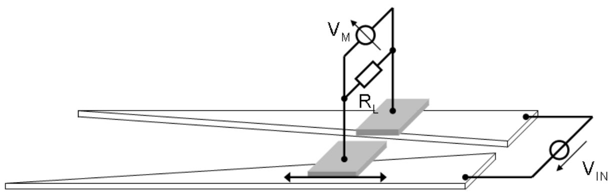

Fig. 6. Measurement setup for voltage reference method

For the load resistance, a value of 10kΩ was chosen. For a frequency range from 2 to 5 MHz, the values shown in figure no. 9 were measured (with a given input voltage of 5 V):

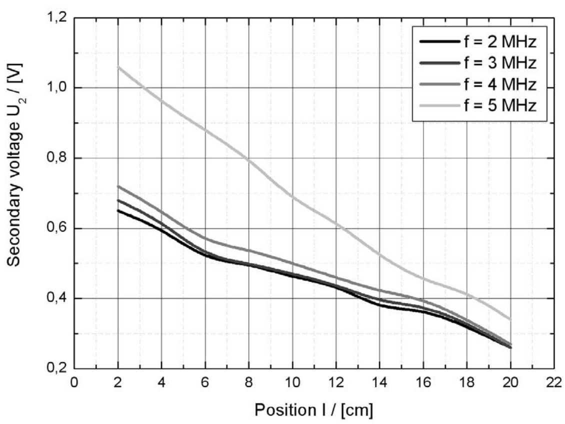

Fig. 7. Measured voltage values in MHz range

The higher slope found in the 5 MHz range relates to a resonant behavior, which is caused by the parasitic inductances of the transmission line and the probe.

4.2. Frequency reference

Furthermore, the frequency dependency as it is described in circuit variant 2 was to be shown in a practical setup.

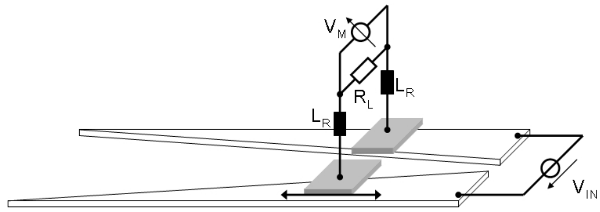

Fig. 8. Measurement setup for frequency reference method, secondary side

The secondary side was equipped with two serial inductances of 100µH each, allowing a resonance voltage peak to be measured across the load resistance. By measuring the spectral position of this peak, one secondary side is able to determine its own absolute position.

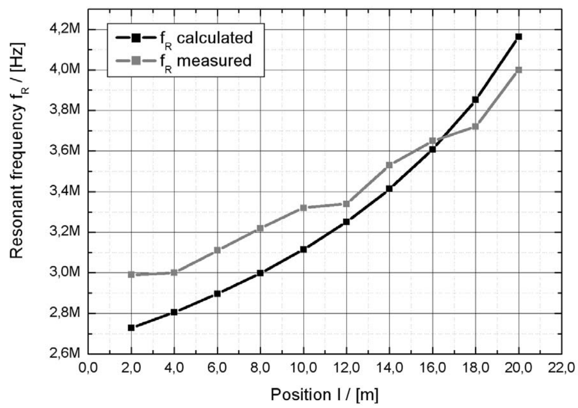

Fig. 9. Resonant frequency drift with constant secondary side impedance

To show the detectability of the number and position of attached nodes from the primary side, the rail has been equipped with two participants, each with a serial circuit of two inductances (100 µH) and a relatively small load resistance (120 Ω).

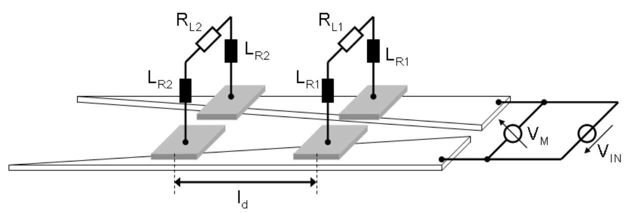

Fig. 10. Measurement setup for frequency reference method, primary side

The voltage on the primary side has been measured with the oscilloscope while tuning the frequency of the generator. The measurements show a voltage minimum (current maximum, respectively) in case of a matching resonant frequency for each participant, leading to two local voltage minima in this case. The resonant frequency difference can be related to the distance between the two nodes, giving the following result:

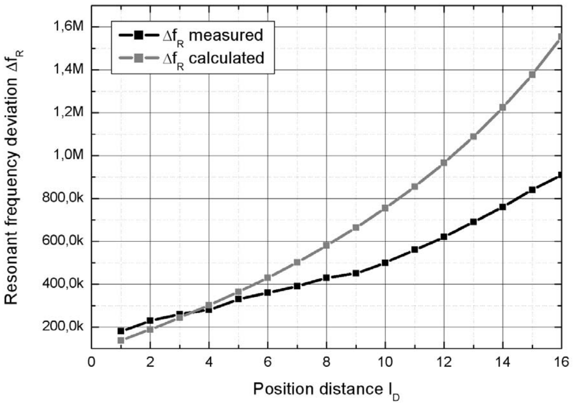

Fig. 11. Resonant frequency difference between to positions of distance l_D

5. Conclusions

It has been shown that position estimation on a contactless rail system can be performed by measuring the voltage drop or the resonant frequency on the secondary side, e.g. every participant in a linear aligned network is able to detect its position. While the voltage measurement is a strictly simple approach, measuring the resonant frequencies not only allows a position estimation on the secondary side, but also an estimation of the number of secondary sides and their positions from the point of view of the primary side. In a contactless operating network like it is given by the application, this method therefore is preferred to be used for location based services. In contrast to commercially available linear position detection systems using inductive or capacitive methods, the proposed solution also works for a large number of secondary side pickups which can be removed and replaced. The measured values have shown good accuracy compared to the calculations, although the setup was no high precision system and ideal components were used for the calculations.

7. References

[1] Hongyang Chen, Pei. Huang, Hing Cheung So, Sezaki K., "Mobility-Assisted Position Estimation in Wireless Sensor Networks", IEEE International Conference on Parallel and Distributed Systems, 8-10 Dec. 2008, Page(s):607 - 614

[2] H. U. Meyer, "An integrated capacitive position sensor", IEEE Transactions on Instrumentation and Measurement, Volume 45, Issue 2, Apr. 1996, Page(s):521 - 525

[3] M. Rahal, A. Demosthenous, "A readout system for inductive position sensors", 18th European Conference on Circuit Theory and Design, 27.-30. Aug. 2007, Page(s):958-961