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DEPARTMENT OF NETWORKED SYSTEMS AND SERVICES

Improvements in Analytical Wideband Impedance Matching and Visible Light Communication

Thesis Booklet

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Summary of Theses and List of Related Publications

Thesis I. - Overcoming the Realization Problems of Wideband Impedance Matching Network Synthesis

Introduction

The Bode-Fano method provides the low-pass filter prototypes (impedance matching network prototype). As the majority of impedance matching tasks require band-pass response, frequency transformation is required [4]. At this point the matching network designer can freely chose between several realization options. One can choose: lumped element matching network, quarter-wave shunt-stub transmission line network or quarter-wave coupled line transmission line network. In case of lumped element networks the reactant elements are substituted by either a parallel or series resonant L-C structures. In transmission line networks mainly admittance or impedance inverters are used. Impedance and admittance inverters are also useful for altering the generator impedance for an arbitrary value (e.g. $50\,\Omega$). I discovered that during the synthesis of impedance or admittance inverters an important issue can occur: non-realizable matching network element values. This equally affects admittance and impedance inverter synthesis. My aim in this thesis is to find and eliminate the origins of non-realizable networks. I achieved this through the systematic inspection of all the input and internal parameters of the admittance/impedance inverter synthesis process. Fortunately, I found some constraints which have proven to be useful for avoiding non-realizable networks. Under the *non-realizable* term I mean admittance/impedance values smaller than or equal to zero, or the values are not purely real. These realization constraints can also be inserted into an automated matching network synthesis algorithm. As an application example, I created an algorithm for finding the best acceptable and also realizable matching network in a MATLAB environment. With this algorithm the end-user can achieve better matching results, without needing to manually reiterate through several parameter values with a trial-and-error approach.

Thesis I/A. - Realization Constraints of Admittance Inverters based on Shunt Stub Transmission Lines

Admittance inverters are used when series R-L-C loads are matched to an arbitrary purely real generator impedance on a pre-defined frequency range (bandpass frequency response). In order to avoid non-realizable (complex or negative) matching network values, I present the results based on the analytical calculations shown in my Thesis. If parameter $d > \frac{\delta}{2}$ then all impedance values are purely real [5, 1]. The rules for avoiding negative impedance values are a bit more complex.

1. If $Y_{2,3}$ is purely real, then $Y_{2,3} > 0$ without any further condition.
2. If $d_\mathrm{p} < 1$ then $Y_2 > 0$ without any further condition. However, if $d_\mathrm{p} > 1$ then $Y_2 > 0$ only if the necessary condition is fulfilled:
$$U < \frac{U}{2\,d_\mathrm{p}} + 2\,\frac{(d_\mathrm{p} - 1)}{d_\mathrm{p}} J_{2,3}. \tag{1}$$
3. The sufficient condition for $Y_3 > 0$ is:
$$d_\mathrm{p} \frac{\delta}{k_{1,2}^2} < \frac{R_\mathrm{L}}{\delta\, D\, R_\mathrm{g}}. \tag{2}$$

Thesis I/B. - Realization Constraints of Impedance Inverters based on Coupled Transmission Lines

Impedance inverters are used when parallel R-L-C loads are matched to an arbitrary purely real generator impedance on a pre-defined frequency range (bandpass frequency response). To avoid non-realizable matching network values, I presented the results based on the analytical calculations. If parameter $d > \frac{\delta}{2}$ then all impedance values are purely real. This result is similar to the one I got at the admittance inverter analysis. The rules for avoiding negative impedance values are a bit more complex, therefore it can be found summarized below. As a rule of thumb, the arbitrary parameter d_p should be less than or equal to 1. But this is neither a necessary, nor a sufficient condition. The complete system of requirements for the coupled line impedance values to be larger than 0 is presented here.

1. $\left(Z_{0-\mathrm{even}}^{\mathrm{a}}\right)_{2,3} > 0$ is unconditionally fulfilled for any $d_\mathrm{p} > 0$ values.
2. $\left(Z_{0-\mathrm{odd}}^{\mathrm{a}}\right)_{2,3} > 0$ must be separated into three further cases.

- If $0 < d_\mathrm{p} \leq 1$, then $\left(Z^\mathrm{a}_{0-\mathrm{even}}\right)_{2,3} > 0$.
- If $d_\mathrm{p} > 1$ and $U > K_{2,3}$ then $\left(Z^\mathrm{a}_{0-\mathrm{even}}\right)_{2,3} > 0$, where $U = R_\mathrm{L}\,\tan\left(\Theta_1\right)\frac{\delta}{k^2_{1,2}}$.
- If $d_\mathrm{p} > 1$ and $U < K_{2,3}$ and $1 < d_\mathrm{p} < \frac{U-2\,K_{2,3}}{2\,(U-K_{2,3})}$ then $\left(Z^\mathrm{a}_{0-\mathrm{even}}\right)_{2,3} > 0$.

3. $\left(Z^\mathrm{b}_{0-\mathrm{even}}\right)_{2,3} > 0$ is unconditionally fulfilled for any $d_\mathrm{p} > 0$ values.
4. $\left(Z^\mathrm{b}_{0-\mathrm{odd}}\right)_{2,3} > 0$ if $\left(Z^\mathrm{b}_{0-\mathrm{even}}\right)_{2,3} > 2\,K_{2,3}$.

Thesis I/C. - Algorithmic Implementation of the Bode-Fano Method Demonstrated with Admittance Inverters using the Suggested Realization Constraints

The realization constraints alone does not actively aid efficient matching network synthesis. After an input parameter combination, which resulted a non-realizable network the parameters must be adjusted manually and the whole process ends up as a series of trial-and-error iterations. Therefore, I suggested an efficient algorithm which pre-filters the non-realizable results, before the complete synthesis process is done [1]. Without this pre-filtering step, all parameter combinations must be analyzed separately, resulting in slow synthesis process (even if realization is impossible). Instead, the non-realizable networks are filtered out before the whole synthesis process, resulting in reasonably faster network synthesis.

Apart from, the arbitrary input parameter values (d_p, r) I declared a variable relative bandwidth parameter b. This parameter aids the matching network designer to find the acceptable frequency response (required minimal bandwidth). Although, generally the required matching bandwidth is a static constant defined before the matching process is initiated, in the case of the Bode-Fano method there are situations where a narrower required bandwidth (smaller b) is non-realizable and a higher b value is. For this reason, I set up parameter b to be adjustable. I implemented the automated matching algorithm in MATLAB and presented the result of a series R-L load matching task as an example.

Using my suggested automated matching algorithm, the burdensome trial-and-error approach for finding the acceptable matching network is substituted with a significantly more efficient solution.

Thesis I/D. - Alternative Matching Approach for On-Chip Antennas used in UHF RFID Applications

Without a doubt, the Bode-Fano method does have its' limitations. In cases where the load quality factor is high ($Q > 30$) and the aimed frequency range is relatively large ($b > 1\%$) the synthesis process can potentially fail, without finding an acceptable result. For loads that are not well substituted by a single reactance load, the Bode-Fano method cannot be utilized. This is the case for ultra-small form factor, electrically small, On-chip Antennas (OCA). For matching OCAs, alternative antenna design method is needed, presented in [2]. Without adding an additional matching network, altering the antenna geometry and adding a slow-wave structure resulted in better impedance matching and better radiation performance (details are shown in [2]).

Thesis II. - An Alternative Approach to Noise Reduction in Visible Light Communication (VLC) Systems Deployed in Vehicle-to-Vehicle (V2V) Communication Applications

Introduction

In the last few years, VLC started to spread as the 5G initiative delegated it as a viable alternative to high-speed, local, secure RF communication. As modern lighting devices are based on semiconductor technology (LED, LASER), this gave an important boost for the area of VLC. Using VLC for V2V applications has spread in the last few years [6]. Even special applications, like V2V communication became possible, as modern vehicles are equipped with LED based lamps. This thesis focuses on a novel approach for enhancing the noise reduction performance of VLC links used in V2V applications. I proposed a differential 2x2 space-divided (2x2 D-SD) method for reducing common-mode noises in the VLC-V2V channel [7]. I made real-life measurements regarding the nature of optical noises, that may occur in the urban VLC-V2V channel. Based on the measurements, I built the demonstrative measurement setup and conducted several common-mode noise measurements and compared the performance of my suggested solution, with the conventional common-mode transmission (2x2 C-SD). My results showed, that my solution performed better, when common-mode noise was significant for shorter transmission distances (under 10 meters) [3].

Thesis II/A. - Common-Mode Noise in V2V-VLC Communication

My first assumption was regarding the presence of noises in the V2V-VLC channel under badly lit environmental conditions. I assumed that the major noise source is the light emitted by public lighting. Assuming, that the vehicles are far away from the public lighting, the light absorbed on the vehicle's chassis reaches both the VLC receivers simultaneously, when they are placed on the rear of the vehicle near each other. I suggested a dual, spatially separated receiver structure and a differential amplifier to cancel out common-mode noise emitted by public lighting. I confirmed these assumptions with real-life road measurements, which I carried out in an urban environment at night using a Honda Civic X car. My measurements confirmed that: the VLC-V2V channel does contain common-mode noise emitted from public lighting and the differential receiver structure significantly reduced the amount of common-mode noise, as expected (up to 50 % in some situations).

Thesis II/B. - Simulation of Common-Mode Noise Reduction in V2V-VLC Application

For the sake of more exact comparison with the already widely used common-mode transmitter-receiver VLC-V2V structures, I introduced the simplified mathematical model of the 2x2 D-SD and 2x2 C-SD arrangement. I included thorough investigations regarding the advantages and disadvantages of the differential transmission method using a simulation environment I implemented in MATLAB. I compared my 2x2 D-SD solution under several conditions, including: overlapping between light beams (crosstalk), balanced and unbalanced common-mode and non-common-mode added noise. I also presented the versatility of the D-SD solution, that it efficiently reduces common-mode noise without using optical domain filters or electrical domain filters. I showed the application limitations and criteria of the 2x2 D-SD arrangement. I presented several simulation arrangements for a wide range of signal and noise scenarios. I confirmed with simulations, that the 2x2 D-SD solution performs well under situations where the amount of common-mode noise is close to the level of the utile signal. I presented the disadvantageous effects of overlapping light beams at the receiver side with the simulation environment.

Thesis II/C. - Measurement Results of the Proposed Common-Mode Noise Reduction Technique

Based on the preliminary simulation results and arrangements, I built a complete 2x2 VLC-V2V setup using licensed automotive grade LED lamps (unlike the majority of published works, so far) and my custom designed VLC receivers. The quantity I used for rating the quality of the connection was the Q-factor I extracted from the eye-diagram. I also did approximate BER calculations, based on the Q-factor values. I conducted measurements at several TX-RX distances, with and without in-band common-mode noise source. I compared the 2x2 D-SD solution with the common 2x2 C-SD solution (where both transmitters send the same optical signal and receivers sum the incoming optical power). My results showed great correspondence with the simulation results. I measured that for shorter distances the 2x2 D-SD transmission performed significantly better, than for larger TX-RX distances, due to the overlapping light beams. 2x2 D-SD excelled at noise reduction compared to

2x2 C-SD, in those setups where common-mode noise level was relatively high. I was able to give a rule of thumb for those use cases, where 2x2 D-SD performs better than 2x2 C-SD. Finally, I gave a possible solution for reducing crosstalk between light beams, by applying Field-of-View (FOV) limiters on the receivers. By attaching FOV limiters at the receiver side, the amount of crosstalk I measured, had reduced significantly enhancing the quality of connection and lowering BER values, as expected.

Journal papers

[1] Balázs Matolcsy and Attila Zólomy. "Overcoming the Realization Problems of Wideband Matching Networks". In: *INFOCOMMUNICATIONS JOURNAL* 10.4 (2019), pp. 31–36.

[2] Balázs Matolcsy and Attila Zólomy. "Designing an Efficient Ultra Small Form Factor On-Chip Antenna for UHF RFID Application." In: *Radioengineering* 29.2 (2019).

[3] Balázs Matolcsy, Eszter Udvary, and Ágoston Schranz. "Common-Mode Noise Reduction with Space-Divided Differential 2x2 VLC for V2V Applications". In: *Optical and Quantum Electronics* (2021).

Conference papers

[4] Balázs Matolcsy, Attila Zólomy, and Eszter Udvary. "Wideband impedance matching for VCSELs used in Free-Space quantum communication". In: *2016 18th International Conference on Transparent Optical Networks (ICTON)*. IEEE. 2016, pp. 1–4.

[5] Balázs Matolcsy and Attila Zolómy. "Practical Realization Rules for Wideband Impedance Matching using the Double-Terminated Filter Synthesis Method". In: *2018 11th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP)*. IEEE. 2018, pp. 1–5.

[6] Tamás Szili, Balázs Matolcsy, and Gábor Fekete. "Water pollution investigations by underwater visible light communications". In: *2015 17th International Conference on Transparent Optical Networks (ICTON)*. IEEE. 2015, pp. 1–4.

[7] Balázs Matolcsy and Eszter Udvary. "Common-mode Noise Rejection in V2V/V2I Communication Based on Differential VLC Transmission". In: *2020 12th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP)*. IEEE. 2020, pp. 1–6.