Automated design of IoT Wi-Fi FSS filter

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Abstract. This work is presenting a technique of automated design of a Frequency Selective Surface aimed at shielding wireless communication under a very new standard of IEEE 802.11ah. This standard is primarily focused on rapidly growing network of communicating electrical devices called Internet of Things. Shielding of such a communication can be, in certain situations, very important for elimination of the possibility of eavesdropping.

1 Introduction

The standard from the Institute of Electrical and Electronics Engineers (IEEE) with the label of 802.11ah is a quite hot topic in the field of the Internet of Things (IoT). For the purpose of communication between even very small electrical appliances a very special energy saving way of communication has been developed.

The world of IoT is full of electrical devices, sensors, accessories, wearables, security elements, various appliances utilizable in Smart Home (for instance lighting, cooking, heating) and also agriculture monitoring, industrial automation and smart metering. The number of mentioned devices is supposed to raise rapidly in the near future what is related with potentially significant security risks.

Therefore the main goal of this study is aimed at possible ways of shielding communication under this standard against eavesdropping outside a room or a building.

This study is partially based on the previous work [1] where the goal was to reflect wireless communication under older standard IEEE 802.11b,g.

This article includes the following content: section 2 contains brief description of IEEE 802.11ah. In section 3, there are very simply described some possible ways of shielding of this type of wireless communication. Section 4 informs about a chosen way of optimization of a filter based on a Frequency Selective Surface. And finally Section 5 presents synthetic results and section 6 concludes the whole idea presented in this study.

2 IEEE 802.11ah

The IEEE standard of 802.11ah, also called "Wi-Fi HaLow", has a great potential of usability in the area of IoT because of two main reasons [2]:

- Low power consumption thanks to a native power saving mechanism with sleep modes (should consume much less energy than Bluetooth or Wireless-Fidelity (Wi-Fi) of earlier standards b, g, a or n)

- Long range (can penetrate walls much more easily), the penetration and range of various Wi-Fi standards is depicted in Figure 1.
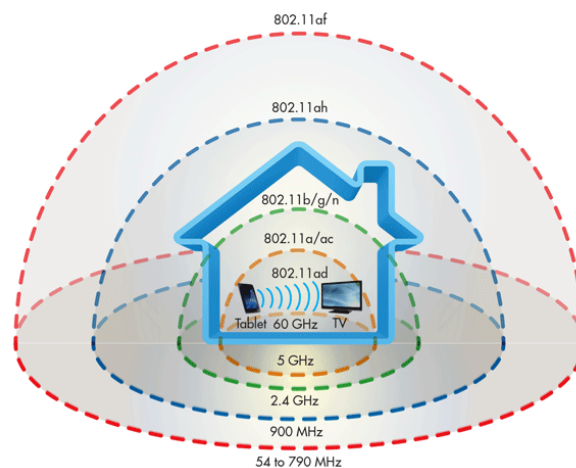

Figure 1. Comparison of different Wi-Fi ranges [3].

Both items mentioned above are based on the key technological features of IEEE 802.11ah [4]:

- Sub 1 GHz frequency

- Design of new Physical Layer (PHY layer) and Media Access Control Layer (MAC layer). These new layers include several modifications with respect to consolidated IEEE standards. The IEEE 802.11ah MAC layer incorporates most of the main IEEE 802.11 characteristics, adding some novel power management mechanisms.

- Typical range of IEEE 802.11ah is 100 – 1000 m

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- Transmission power is from <10 mW to <1 W (depending on the country's regulations)

- Battery operation should be from months to years (also thanks to long sleeping periods)

The mentioned standard is very new. It was standardized and introduced in January 4 2016 [5] (the first IEEE 802.11 standard was released in June 1997). The first certified devices should come soon (probably in 2017 or 2018). Due to these data, the topic of this study is unique and potentially very important and interesting from the point of view of secure communication.

3 Shielding

Considering wireless communication between electrical sensors or generally devices using IEEE 802.11ah, the first idea of how to shield a communication in a room, in a small building or area is to use

A) a very simple Faraday cage or

B) a very specific and hard to develop wallpaper reflecting only a desired frequency range.

3.1 Faraday cage

Faraday cages are named after the English scientist Michael Faraday. Faraday shield (cage) is an enclosure made from a conductive material or by a mesh of such material to block electric fields.

These shields – cages can be used to protect different kinds of electronic equipment from electrostatic discharges. They cannot block magnetic fields like Earth's magnetic field, but they can protect the interior from electromagnetic radiation coming from the outside. An external electrical field leads to rearrangement of the charges, and this cancels the field inside. Electric fields (applied externally) create forces on electrons in the conductor, creating a current, which will further result in charge rearrangement. The current will cease when the charges rearrange and the applied field inside is cancelled [6].

This approach is cheap but has several very negative side effects. First of all, whole frequencies coming to or from a cage are reflected, generally:

- Global System for Mobile (GSM)

- Universal Mobile Telecommunications System (UMTS)

- Long-Term Evolution (LTE)

- all frequencies of Wi-Fi (sub 1 GHz, 2.4 and 5 GHz)

- Bluetooth

- and possibly also the visible light if not using a dense mesh

This approach may go against the original aim to use IEEE 802.11ah in longer distances.

3.2 FSS

Frequency Selective Surfaces (FSSs) are important spatial filters, which can efficiently filter desired band of frequencies. Therefore these can play a significant role in electromagnetic related problems.

Frequency selective surfaces can be used and adjusted to prepare a structure reflecting just a desired narrow range of a spectrum.

To briefly sketch the history, the beginning of FSS relates to Ben A. Munk who was the guru of this approach [7]. In the last decade, the idea of FSS has spread out into many applications. Example of a band-pass FSS is in [8] where the goal was to transmit GSM signals through energy efficient windows. One of the first FSS absorbers was presented by Salisbury and Jaumann [9]. Great research has been already done in the field of FSS including also the analysis of frequency characteristics of dielectric period structures [10] and another analysis of characteristics of dielectric grating of left-handed and right-handed materials [11]. FSS are also used in the antenna theory and experiments like analysis of ultra wide band planar monopole antenna and its design [12].

Back to shielding: this second idea of how to shield the communication (using FSS) is to use a special pattern/wallpaper selectively attenuating just the frequency range used in IEEE 802.11ah.

With respect to the design, rules and law of various countries the frequency range for Europe is 863 – 868 MHz (for example in USA it is 902 – 928 MHz and in China it is 755 – 787 MHz) [13]. Figure 2 presents the ranges in more detail.
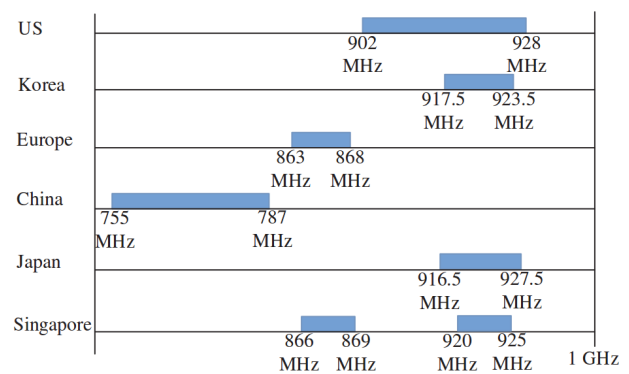

Figure 2. Sub 1 GHz spectrum specified in the IEEE 802.11ah channelization [13].

The standard of IEEE 802.11ah is operating in sub-gigahertz frequencies in comparison with traditional IEEE 802.11b or IEEE 802.11g working at 2.4 GHz and IEEE 802.11a working at 5 GHz.

The schema of a typical FSS structure: simple cross and a Jerusalem-cross is presented in Figure 3. Both models consist of simple rectangular elements. Theoretically, the second geometry may have better reflection. Moreover double-layer should provide a more narrow band-stop filter. Several comparisons have been presented in [14].
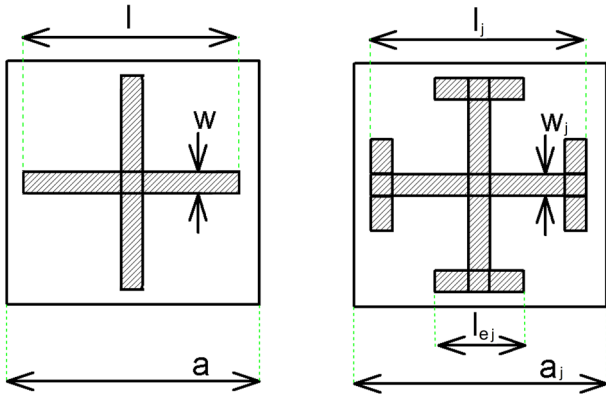
Figure 3. Schema of a cell containing the simple cross (on the left) and the Jerusalem-cross (on the right).

In Figure 3, a and a_j represent the width and height of a cell (a cell is just one square element of the whole structure of FSS; index j relates to the structure depicted on the right: the Jerusalem-cross), l and l_j is the total width and height of the cross, w and w_j is the width of an arm and l_{ej} represents the length of the bar connected to the end of an arm of the Jerusalem-cross.

There is a special software suitable for optimization of FSS elements. It is FSSMR software [15], which was developed at Tomas Bata University in Zlin and which analyses the planar periodic structures and tries to optimize them with respect to defined optimization goals. Therefore this software is suitable for estimation of proper values of design variables (a_j, l_j, w_j, and l_{ej}) to meet the optimization goals (and thus to reflect the desired frequency band in this case of IEEE 802.11ah).

There are also some shortages in this approach. One of the most questionable aspects of the FSS approach is the influence of the angle of incidence which must be also examined. Another problem is with windows when attempting to secure a room against transmitting sub 1 GHz frequencies outside the room.

4 Optimization

A frequency range, an initial geometry with design variables (e.g. width and height of the arms of the cross) and optimization goals must be set before performing the optimization of an FSS filter.

The transmission coefficient depends on frequency and other parameters forming the parameter vector of the filter which specifies the geometry (defined by design variables). An optimization method searches for the set of parameters which satisfies the given objectives, at least approximately, being thus in a certain sense optimal.

An optimization goal is defined by a frequency range where the transmission coefficient must be lower or greater than a defined threshold value.

In our experiment three optimization goals were modelled (also graphically presented by green color in Figure 4 together with results of the initial configuration):

Table 1. Description of design parameters related to the geometry of the Jesrusalem-cross FSS filter (see Figure 3).

Var.	Description	Initial Value	Lower Bound	Upper Bound
a_j	The width and height of a cell [m]	0.15	0.1	0.2
w_j	The width of an arm [m]	0.0055	0.001	0.010
k_{1j}	The width parameter ($k_{1j} = l_j/a_j$)	0.85	0.7	1.0
k_{2j}	The length parameter ($k_{2j} = l_{ej}/l_j$)	0.35	0.2	0.5

1. To transmit frequencies from 0.1000 to 0.8222 GHz (threshold: -2.5 dB)

2. To reflect frequencies from 0.8223 to 0.9088 GHz (this range relates to the Q factor equal to 10, $f_{stop\ range} = f_c/10 = 86.55 MHz$; threshold: -20.0 dB)

3. To transmit frequencies from 0.9089 to 3.0000 GHz (threshold: -2.5 dB)
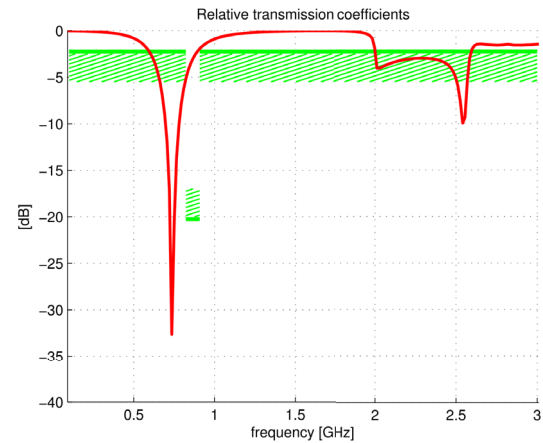

Figure 4. Transmission coefficients of the initial geometry of the FSS IEEE 802.11ah filter.

The initial values of design parameters with lower and upper bounds were guessed (by the earlier professional experiences with FSS filters) and they are mentioned in Table 1 where $l = ka$, $l_j = k_{1j}a_j$ and $l_{ej} = k_{2j}l_j$.

In this work, optimization was performed numerically using an implementation of local optimizer of Levenberg-Marquardt (a possible alternative is *fmincon* [16] or *fminsearchbnd* [17] which can be directly used in Matlab, evolutionary algorithms are another possible way).

The settings of the optimization process:

- Optimization technique: Levenberg-Marquardt

- FunTol = 10^{-3}, this represents the threshold tolerance

- MaxIter = 100, this constant defines the maximal number of iterations

- NormStep = 0.06, this is the constraint on maximal norm of a step

- Constraints on design variables a_j, w_j, k_{1j} and k_{2j} respect the lower and upper bounds mentioned in Table 1

- Cost function uses the method of moments [7, 18] to analyse and estimate the FSS transmission coefficients

All computations by optimization were based on perpendicular angle of incidence only.

In this study, FSSMR software [15] was used. It was developed at Tomas Bata University in Zlin and it analyses the planar periodic structures and tries to optimize them with respect to the optimization goals.

5 Results

The optimization procedure results in a filter which suppresses well the central channels. The attenuation is below -20 dB what can be considered as a very good filter. The final transmission coefficients are presented in Figure 5. The process of optimization in Matlab took at about 5 hours using an average computer (mainly depends on the amount of computed frequency points and the density of mesh cells in computation).

There is also some kind of an unwanted low subsidiary attenuation between 2.5 and 3.0 GHz.
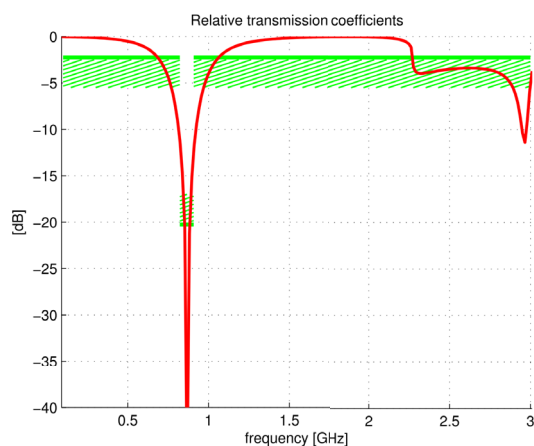

Figure 5. Transmission coefficients of the optimized geometry of the FSS IEEE 802.11ah filter.

The optimized values of design parameters of Jerusalem-cross FSS filter are presented in the list below:

- $a_j = 0.132m$

- $w_j = 0.007m$

- $k_{1j} = 0.85$

- $k_{2j} = 0.35$

Furthermore, from the design parameters the lengths l, l_j and l_{ej} can be computed in the following way:

- $l_j = k_{1j}a_j$; $l_j = 0.1122m$ (the total width and height of the Jerusalem-cross)

- $l_{ej} = k_{2j}l_j$; $l_{ej} = 0,03927m$ (the total length of the outer arms)

6 Conclusion

A very new standard for wireless communication suitable for the Internet of Things, IEEE 802.11ah, has been introduced in this preliminary study together with possible ways of how to shield communication under mentioned standard. A theoretical concept of a wallpaper with a deep practical impact has been revealed. A technique of how to generate an optimized geometry of an FSS filter with adaptation to the narrow specific range of frequencies used in IEEE 802.11ah has been presented. Also, some shortages of this approach have been described.

The boom of the Internet of Things is coming. It can make life simpler (like other technologies in the history), but it also contains a great portion of a threat of abuse. This article points this out.

Further analysis with practical experiments and measurements are proposed as a possible further work in this domain.

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