Mathematical Model of a Compact Dual Band Implantable Antennas for Telemedicine Monitoring Devices

Zafar Iqbal[†], Tahreem Saeed[†], Ahsan Humayun[†] and Tariq Rafiq[†]

[†]Department of Computer Science, COMSATS University Islamabad, Sahiwal Campus, Punjab, Pakistan.

Summary
Wireless connectivity is the most important concern of all upcoming technologies like healthcare applications of internet of things (IoT) and it is only possible using sophisticated antennas. Biological products such as implantable and wearable biosensors are widely used in healthcare applications in which antennas are integrated with them that helps biosensor in remote observation of sensitive patients. These biosensor antennas are designed in such a way that they may conserve minimum energy giving lesser loss to biosensors battery. Dual band antennas are widely proposed for biosensors that switches between two medically reserved frequency bands i.e. Medical Implant Communication Services (MICS (402-405MHz)) and Industrial Scientific Medical (ISM (2.4-2.48GHz)) that conserves overall energy of biosensor. As the antennas designed for these biosensors are the most critical module to get intact with biosensor, therefore, these antennas need to be tested before implementation. Hence, in this paper, formal methods are used to formally specify and verify the biotelemetry antenna's radiation patch that will operate on two bands. VDM-SL language is used to specify and validate the radiation patch and the return loss offered by antenna and then the entire model is implemented, verified and validated using VDM-SL toolbox.

Key words:
Biosensor Antennas, Biotelemetry Products, Miniaturized, Serpentine, Radiation patch, MICS, ISM, Formal Methods, VDM-SL

1. Introduction

Microstrip antennas have numerous compensations and hindrances over other antennas such as low cost, small size, easy fabrication, low power gain, fine bandwidth [1]. Microstrip patch antennas are the most preferable antennas for light-weight applications, such as in ballistic missiles, aircraft systems, aerospace, mobile systems, biosensors etc. [2-3]. Multiple applications have various implementation and frequency requirements. Dual frequency band microstrip antennas are widely used because of their switching mode between two different frequency bands and this switching (between transmission and reception mode) make them able to preserve energy [4].
In this paper, the basic concern is to verify and validate a biosensor's antenna. So, firstly to have a brief description of a biosensor, we can say that a biosensor is a methodical device that is used for the recognition/analysis of an analyte by combining a biological component along with physicochemical sensor module. In recent studies, implantable antennas are getting popular and are intended for frequent wireless biotelemetry applications such as implantable drug pumps, and nerve signal recorders [5], cochlear implants, artificial eyes, cardiac and brain pacemakers [6]–[8]. Research shows that microstrip patch antennas are implemented with spirals and serpentines patches and are found to be most suitable for MICS band process [9].
This paper proposed a formal description of a small sized serpentine radiation patch for biotelemetry antennas that would operate on MICS and ISM bands proposed in literature [14]. Formal specification of antenna's patch is implemented by using formal methods.
Formal methods are mathematical techniques that are widely used to prove the correctness, verification and validation of hardware and software systems [10]. There are several formal languages e.g. VDM, B, Z etc. used to specify any system's model. These methods verify the system's functional and non-functional requirements to prove its validity and correctness.
We use formal methods instead of simulations or other optimization techniques because a simulation only generates some of the possible outcomes against some given test cases. On the other hand, in our previous work [14], simulations of a small sized antenna are done using HFSS but the model presented in that paper was not verified and validated. As biosensor and implantable antennas are very sensitive, therefore the antenna design needed to be proved correct and verified through some intelligent and trusted techniques. Formal methods mathematically prove the correctness and validity of any hardware or software system.
Therefore, in this paper, VDM-SL formal language is used to proof the correctness of the antennas' radiation patch and return loses presented in literature [14]. The antenna is implemented, analyzed and proved correct by using VDM-SL toolbox.

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2. Related Work

When we consider the past studies, we have many biotelemetry antennas designs that are optimized/ implemented using various techniques like Particle Swarm Optimization (PSO), genetic algorithms (GA) and finite-difference time-domain (FDTD). Antenna that is small and is completely implantable durable for continuous monitoring device was proposed or design as an additional for existing continuous patient monitoring systems [11]. Research shows that multiple designs of antennas are considered for numerous practices in medical field but serpentines and spirals shapes are the most optimal shapes for medically used implantable antennas. For this purpose, serpentines and spiral antennas are enthusiastically designed to resonate at the two medically reserved frequency bands that are around 402-405 MHz MICS band and 2.4-2.48 ISM bands [11] that control antennas interferences at the frequency bands. Hence, for the optimization purpose, different algorithms or techniques are applied to design the radiation patches of antennas. In literature [11], particle swarm optimization (PSO) technique was used to model entire antenna and antenna's radiation patch was optimized to radiate at MICS and ISM bands. In paper [12], the mixture of finite element-boundary integral (FE-BI) technique was said to be suitable for modeling conformal antennas on doubly curved surfaces was established. The paper [13] described a conformal finite-difference time-domain (CFDTD) software package, and presented its uses to Radio Frequency antennas and microstrip circuit constituents.

Various techniques can be applied to model different type of antennas and in this paper, we used formal mathematical based models to describe the correctness of antenna's radiation patch and the entire model presented in literature [14]. This patch is formally verified by using VDM-SL toolbox and is proved correct to be used with any medically suitable substrate and superstrate of size 20mm by 20mm (length in mm by width in mm).

3. Formal Model of Antenna Radiation Patch

A formal verification of dual band implantable serpentine radiation patch antenna is done in this paper. This design of the patch can be used in combination with different medically approved substrates and with standard radiation environments. The patch parameters are optimized by using the parametric constraints given in literature. This patch can be used on the 20mm length by 20mm width substrates. Figure 1 shows the 3D design of the radiation patch that is formally verified and corrected by using VDM-SL formal specification language.

VDM-SL language is used in this paper for the detailed level specification of the radiation parameters of the radiation patch of the antenna. The static and dynamic properties of the antenna are specified by defining static types and state invariants etc. The serpentine patch is modeled statically because this model of the antenna is also simulated and the parameters support the dual bands exactly.

Firstly, the values are defined to explain the upper and lower bounds of the MICS and ISM bands to explain the ranges of these reserved bands.

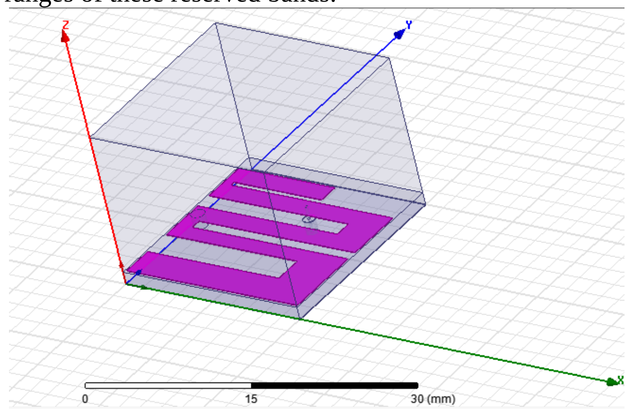

Fig. 1 3D design of serpentine radiation patch

```
values

MICS_min = 402;
MICS_max = 405;
ISM_min = 2.4;
ISM_max = 2.48;
```

The type of the patch's material, lengths and widths is defined as a general type "Copper", MICS and ISM bands are then defined and given a type real. After that, the standard plane is defined as a composite type having three axis i.e. x, y and z of real type.

```
types

Copper = token;
MICS = real;
ISM = real;
Coordinates :: x : real
               y : real
               z : real;
```

Then, substrate is defined as a composite type in which length, width and the placement of the substrate material is defined to specify the complete material.

```
Substrate :: length : real
             width : real
             placement : Coordinates
inv mk_Substrate (l, w, -) == l = 20 and w = 20;
```

Invariants are used to specify the limitations on the specific variables or the system type. Here the above invariant is defined on the overall antenna size which limits the antenna size to 20 mm by 20 mm.

The basic concern of this paper is to verify a serpentine patch that is composed of vertical and horizontal rectangles of copper combined together. These lengths and widths directly affect the radiations of the antenna. Rectangles of copper when get excitations radiates energy at specific frequencies. Here we model design this patch in a serpentine shape because this design provides maximum return loss at MICS and ISM bands. So for this purpose, we define material Copper type as token which means that it does not require any further definition. Then horizontal and vertical lengths and widths are defined as real.

These are the types defined for the vertical and horizontal lengths having some lengths and widths.

The connected type describes the specific format of the shape i.e. we first insert vertical then horizontal and so on and are connected to make a serpentine radiation patch.

```
VRLength :: l1 : real
            l2 : real
            l3 : real
            l4 : real
            l5 : real ;

VRWidth :: w1 : real
           w2 : real
           w3 : real
           w4 : real
           w5 : real ;

HRLength :: l1 : real
            l2 : real
            l3 : real
            l4 : real   ;

HRWidth :: w1 : real
           w2 : real
           w3 : real
           w4 : real ;

VerticalRectangle :: vrlength : VRLength
                     vrwidth : VRWidth ;

HorizontalRectangle :: hrlength : HRLength
                       hrwidth : HRWidth ;

Connected = VerticalRectangle * HorizontalRectangle
* VerticalRectangle ;
```

A composite type RadiationPatch is defined: in which we describe the material of the patch copper of type Copper, then set of vertical and horizontal rectangles are the parameters of the patch and at last, connected of type Connected is defined that describes the connectivity pattern of these vertical and horizontal rectangles of this serpentine radiation patch.

```
RadiationPatch :: copper : Copper
                  verticalrectangles : set of
VerticalRectangle
                  horizontalrectangles : set of
HorizontalRectangle
                  connected : Connected
inv mk_RadiationPatch (-,verticalrectangles,
horizontalrectangles, -) ==
         forall vr in set verticalrectangles &
         vr.vrlength.l1 = 19.6 and
         vr.vrlength.l2 = 19.6 and
         vr.vrlength.l3 = 19.6 and
         vr.vrlength.l4 = 19.6 and
         vr.vrlength.l5 = 19.6 and
         vr.vrwidth.w1 = 3.3 and
         vr.vrwidth.w2 = 1.77 and
         vr.vrwidth.w3 = 2.12 and
         vr.vrwidth.w4 = 2.12 and
         vr.vrwidth.w5 = 2.12 and
         forall hr in set horizontalrectangles &
         hr.hrlength.l1 = 4.52 and
         hr.hrlength.l2 = 1.69 and
         hr.hrlength.l3 = 3.55 and
         hr.hrlength.l4 = 1.0 and
         hr.hrwidth.w1 = 2.97 and
         hr.hrwidth.w2 = 1.11 and
         hr.hrwidth.w3 = 1.78 and
         hr.hrwidth.w4 = 0.53 ;
```

Invariant: The above mentioned invariants defined the complete structure of the radiation patch. These invariants set the limitations on the vertical and horizontal rectangles and statically model the lengths and widths for each and every rectangle in millimeters. For example, first vertical rectangle has length 19.6 mm and width 3.33 mm and so on and first horizontal rectangle has length 4.50 mm and width 2.97 mm and so on. The invariants on material and connectivity of the radiation patch are not defined because these are not required here. This formal specification describes the complete mathematical model of the serpentine radiation patch for the dual band operations of the biotelemetry antennas.

The dynamic part of the model i.e. antenna, is defined as a state of the entire design. The complete state is composed of substrate radiation patch and two frequency bands.

```
state Antenna of
substrate : Substrate
patch : RadiationPatch
FBand1 : MICS
FBand2 : ISM
inv mk_Antenna(-,-,f1,f2) == MICS_min <= f1 and f1
<= MICS_max and ISM_min <= f2 and f2 <=
ISM_max
end
```

Invariant: The state invariant is defined on the Antenna that specifies that the antenna is bounded to radiate at two bands i.e. MICS and ISM, medically reserved bands.

An operation is defined to explain the return loss over the above described bands. The operation has two parameters i.e. S11 at MICS and ISM bands. It reads two state variables and a post condition is defined and it explains that for all frequencies of MICS and ISM bands the return losses should be minimum 30 dBs.

```
operations

Return_Loss() S11_MICS : real, S11_ISM: real
ext rd FBand1 : MICS
      rd FBand2 : ISM
pre true
post forall f1 : Fband1 & S11_MICS =-30 and forall
f2 : Fband2 & S11_ISM = -30;
```

4. Result and Analysis

Formal modeling and analysis of the antenna design presented in our previous work [14] is verified and is done through VDM-SL toolbox. As described earlier, formal model analysis is required for the detailed examination of any system. So VDM-SL, formal analysis shows that no syntax and type error and no warnings are found during specification analysis.

Invariants on different variables define the accuracy of the model. Warnings and errors are all corrected at the modeling time. Figure 2 depicts the screenshots that provides the proof of the correctness of the formal model of the radiation patch and the complete model of the antenna. In Figure 2, it can be observed that S shows that there is no syntax and T shows that there is no type error in the model of the implantable antenna whereas C indicates that a C++ code is generated against formal model of the antenna and P shows that there is no inconsistency in the verified design.

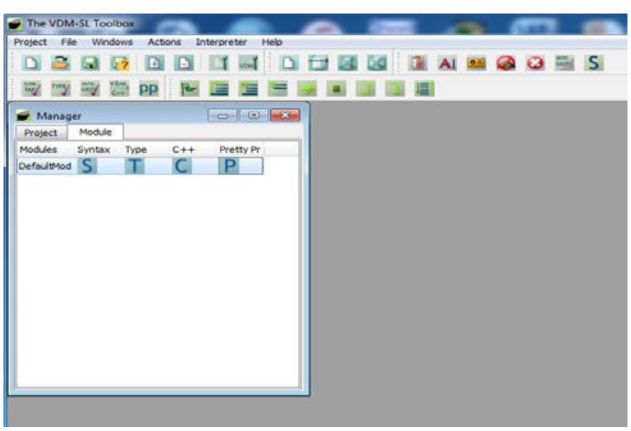

Fig. 1 Screenshot of Formal Verification through VDM-SL Toolbox

5. Conclusion

In this paper, we have verified and validated a formal model of a serpentine radiation patch for the dual band microstrip patch antennas by using VDM, a formal method. This patch will be suitable for all biotelemetry antennas because this model of the patch is optimized and designed to work on the two medically reserved frequency bands i.e. MICS and ISM. These bands can separately be observed to switch between two modes that are transmission and reception. The switching of modes made the device that is using this antenna, energy efficient. For modeling of the patch, we use formal methods that are the mathematical techniques to prove the correctness, consistency, validation and verification of the hardware and software systems. VDM-SL formal language is used to specify the entire model of the serpentine radiation patch and after implementation, the formal model is the proved correct by loading this project into VDM-SL toolbox. VDM-SL toolbox then provides the proof of the correctness of the radiation patch model for the biotelemetry antennas. The radiation patch required the proofed correctness because this can be further used in combination with any kind of medically approved substrates to design any type of biosensor/biotelemetry antennas.

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Zafar Iqbal is pursuing his PhD at COMSATS University Islamabad, Pakistan. Currently, he is serving as Assistant Professor at COMSATS University Islamabad, Sahiwal Campus, Punjab, Pakistan. He received his MS Computer Science in 2008 from University of Engineering and Technology (UET), Lahore, Pakistan. He qualified CISCO Certified Academic Instructor (CCAI) exam with distinction. He also worked in High Performance Computing Lab (HPCL) at Al-Khwarizmi Institute of Computer Science (KICS), UET, Lahore during his master studies. He has supervised various ICT R&D funded projects. Now, he has great enthusiasm towards his research activities. His current research interests include Wireless Ad hoc Networks and its applications, Internet of Things, Internet of Vehicles, and Modeling of Critical Systems using Formal Approaches.

Tahreem Saeed received MS in Computer Science degree in 2017, from COMSATS Institute of Information Technology (CIIT), Sahiwal, Pakistan. She is currently serving as a Lecturer in Department of Computer Science at COMSATS University Islamabad, Sahiwal Campus, Punjab, Pakistan. She received her BS degree in Telecommunication and Networking with distinction of Gold Medal from the same prestigious Institute. She won ICT R&D funding for her research project in BSTN. Her research interests are Wireless Ad hoc networks and its applications, Internet of things, IoV, IoMT, Big Data, Modeling of Systems using Formal Approaches, Various applications and Modeling of Biosensor Antennas.

Ahsan Humayun received the B.S (2014) and M.S (2017) degrees in Computer Science from National Textile University Faisalabad, Pakistan. He joined University of Central Punjab, Faisalabad Campus in 2015 as a Lecturer in Department of Computer Science. Since April 2018, He has been working as a Lecturer in Dept. of Computer Science at COMSATS University Sahiwal Campus, Pakistan. He has published 3 International Journal publications. His main research areas are High Performance Computing, Usage of Data mining techniques and Wireless sensor networks in Healthcare sector.

Tariq Rafiq is currently working as Lecturer at Department of Computer Science, COMSATS University Islamabad, Sahiwal Campus, Pakistan. He received MS degree in Computer Science from Virtual University of Pakistan in 2016. Now he is pursuing his PhD from COMSATS University Islamabad. His research interests include Formal Modeling, Information Systems, Database, Data Warehouse, and Natural Language Processing.