Challenges of Wearable Antenna Design

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***Abstract*—Antenna design for wearable technologies is a challenging task due to the body being in the near-field of the antenna, the highly dynamic nature of the channel and the user acceptance issues. The antenna should be insensitive to the near field effects of the body in order to minimize detuning and to keep its efficiency high which translates to longer battery life time. Preferably, it could have a reconfigurable gain pattern to satisfy almost contradictory requirements of different links and to cope with the dynamic channel conditions. Finally the antenna should be either small or flexible for the users satisfaction while keeping the SAR levels low for safety. This paper discusses the aforementioned requirements in detail and proposes antennas tackling these challenges.**

I. Introduction

Various wearable sensors are being introduced to the market monitoring diverse physiological parameters for fitness tracking of healthy individuals or for diagnosis, therapy and rehabilitation of patients [1], [2]. In the future, it is envisaged that each person is going to be wearing multiple sensors on their body being a part of a Body Area Network (BAN). Some common challenges for the wearable sensors can be listed as achieving robust and quality sensing, high level integration hence low cost production, longer battery life time, and user convenience [3]. Although wearable sensor design is highly multidisciplinary, it can be argued that the careful design of the wireless links is essential to the solution of the previously mentioned goals. These links within the BANs are classified under three categories, in-body, on-body and off-body [4]. Note that BANs consist not only of wearable sensors, but also implantable sensors and off-body gateways. Links formed by an implanted device are called in-body links. On-body links are created between two wearable devices and finally off-body links are formed to connect a wearable to an off-body device. This paper discusses antenna solutions for wearable devices therefore all of these propagation links are going to be taken into consideration.

The network architecture should be designed so that the challenges previously listed for wearable sensor design are addressed e.g. low cost, efficiency and user acceptance. In addition the network should operate and coexist with other networks in similar frequency bands [5]. Here a highly reconfigurable network architecture which opportunistically selects the best possible radiation characteristic for each link is considered. Reconfiguration is proposed in order to improve the reliability and enhance the battery lifetime, however this functionality should not interfere with the user convenience and cost. Therefore the antennas proposed here support radiation pattern diversity along with other requirements. These requirements for each link is discussed in detail in Section II. Solutions proposed by the author is reviewed in Section III. The paper concludes with Section IV.

II. Requirements of a Wearable Antenna

The antenna design is one of the most important elements of the optimum wearable device which should operate reliably for a long period of time without restricting the user activity and causing any behaviour modification.

In order to increase the battery lifetime, the energy efficiency of the device should be improved. Considering the fact that the energy consumed during RF transmission is a high percentage of the overall consumption, decreasing the number of retransmissions and improving the link budget by having higher antenna gain or pattern diversity can directly be translated into longer battery lifetime.

Convenient form factor is also related to the antenna since it is one of the largest elements of the device alongside with the battery. Flexible or small sized rigid antennas are required so that the sensor can be incorporated seamlessly into clothing.

When an antenna is located near lossy human tissue i.e. worn by a person, its frequency response changes and radiation efficiency degrades. In order to avoid these, a body phantom should be included in the design process and the antenna should be electromagnetically isolated from the human body as much as possible with a ground plane. If the antenna is designed to be immune to these near-field effects of the body, the overall system efficiency is going to be maintained.

In addition to being efficient and immune to detuning, the antenna can be re-configurable in order to further improve the system performance. The optimum radiation pattern changes depending on the link to be formed. Directional antennas were proven to perform the best for off-body links [6] whereas a radiation pattern with a null in the vertical plane according to the human body surface is best for on-body links [7]. Vertical polarization is better in launching surface waves [8]. In-body links are trickier since the propagation medium is extremely lossy. Therefore as well as pointing the radiation towards the implant, one should minimize the near-field losses [9], [10]. If a wearable device is intended for more than one type of link or if the device is located in an extremity of a person which is going to lead to a very dynamic channel, then its antenna should satisfy the requirements of more than one type of communication link e.g. both on-body and off-body. Finally the FCC limits for partial-body exposure should be taken into

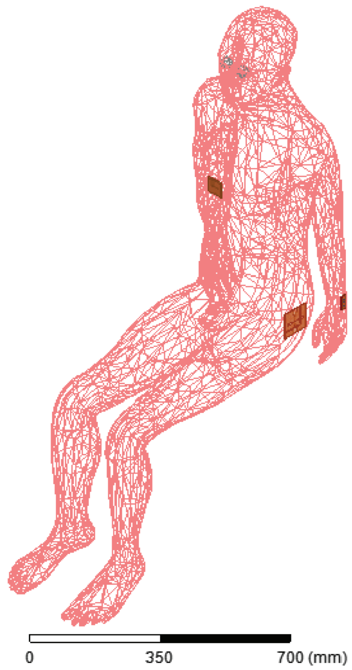

Fig. 1. Wearables simulated on ANSYS human body phantom, Male-4mm accuracy

consideration in all cases [11]. The SAR of all the antennas discussed here are kept well under the 1.6 W/kg limitation averaged over 1g of tissue.

III. Proposed Antennas

Fig. 1 shows various wearable antennas proposed by the author located on a male phantom. A radiation pattern switching patch antenna [12] printed on flexible substrate is located on the chest of the phantom. It has the capability of switching its radiation between a directional pattern which is suitable for securing off-body links and a horizontally omnidirectional pattern which is more suitable for securing on-body links and off-body links where the off-body device is located laterally to the on-body gateway. The antenna is designed to operate in the 2.4 GHZ ISM band. The radiation efficiency is more than 40% for the worst case scenario where the antenna is located on the phantom with no separation between the skin and the ground plane and the off-body mode is enabled. The best efficiency figure of $>52\%$ is observed with 10 mm separation between the skin and the antenna while the on-body mode is enabled. As the separation between the antenna and the skin is changed from 0 mm to 10 mm, the frequency response is observed to be stable for both modes hence the 2.4 GHz ISM band coverage is not disturbed. Moreover the antenna has vertical polarization for the on-body mode which is favourable for NLOS scenarios due to the excitation of stronger creeping waves. This antenna is a flexible antenna and intended to be used on larger areas of the body incorporated into clothing. For a star network architecture where an on-body gateway collects information from multiple sensors scattered on the body and relays that information on to an off-body gateway, this antenna can greatly improve the link quality and reliability. Here the on-body gateway needs to handle the simple switching mechanism which changes the length of a branch shown in Fig. 2 in order to switch the radiation pattern.

A rigid but smaller on-body patch antenna which steers its radiation pattern as the frequency of operation is changed [13], [14] is located on the wrist of the phantom. Here two different radiation modes of a patch antenna are merged in the 2.4 GHz ISM band. These two modes generate two different radiation patterns which have their maximum directivities at $\theta = 0^o$ and at $\theta = 90^o, \phi = 0^o$ respectively. Therefore the beam is steered as the device moves from one mode to another by changing the frequency channel of operation. The simulated radiation efficiency of the antenna is greater than 50% throughout the band even for no separation between the antenna and the skin. The antenna is tested for different separations, and the frequency response has been found to be stable for 0 mm to 10 mm separation. This antenna is intended to be used on a smart watch where the propagation channel is even more dynamic. The optimum radiation pattern is not as clear as the previous case for the on-body and off-body links since the position of the watch according to the intended source is going to change with the movement of the arm. Assuming that Bluetooth low energy standard is used, the instantaneous link quality can be improved by introducing frequency channel pools so that diversity can be utilized during frequency hopping. If a transmission fails, the retransmission should choose a channel which has a different radiation pattern. It has been shown by simulations that the antenna can provide more than 10 dB advantage for the laterally positioned links compared to the case where its vertical directional mode is used.

Another wearable antenna is located on the hip of the numerical phantom in Fig. 1. It is designed to be connected to a repeater which relays the data collected from a smart implant to an off-body gateway. Therefore it needs to secure both in-body links and off-body links. For this purpose, a slot antenna of magnetic-nature is preferred because the high magnetic near fields are less susceptible to dissipation in human body than electrical elements since human tissues have no magnetic losses ($\mu_r'' = 0$). The antenna consists of two slots and a shallow square cuboid cavity backing the slots. The slots are edged onto the opposite square faces of the shallow cavity. They are perpendicular to each other on the horizontal plane. A meandering stripline is used to feed both slots. In order to direct the radiation in one side, the slot on the opposite face is shorted with a switch at its central point and vice versa. It operates in the 2.4 ISM band assuming that the implant will communicate at the same band. Note that according to FCC and ETSI, 402-405 MHz MICS Band is used for implant communications. The in-body propagation loss increases with increasing frequency however resonant size of the antenna decreases. Therefore 2.4 GHz ISM band can as well be suitable if the in-body propagation losses can be compensated with antenna gain.

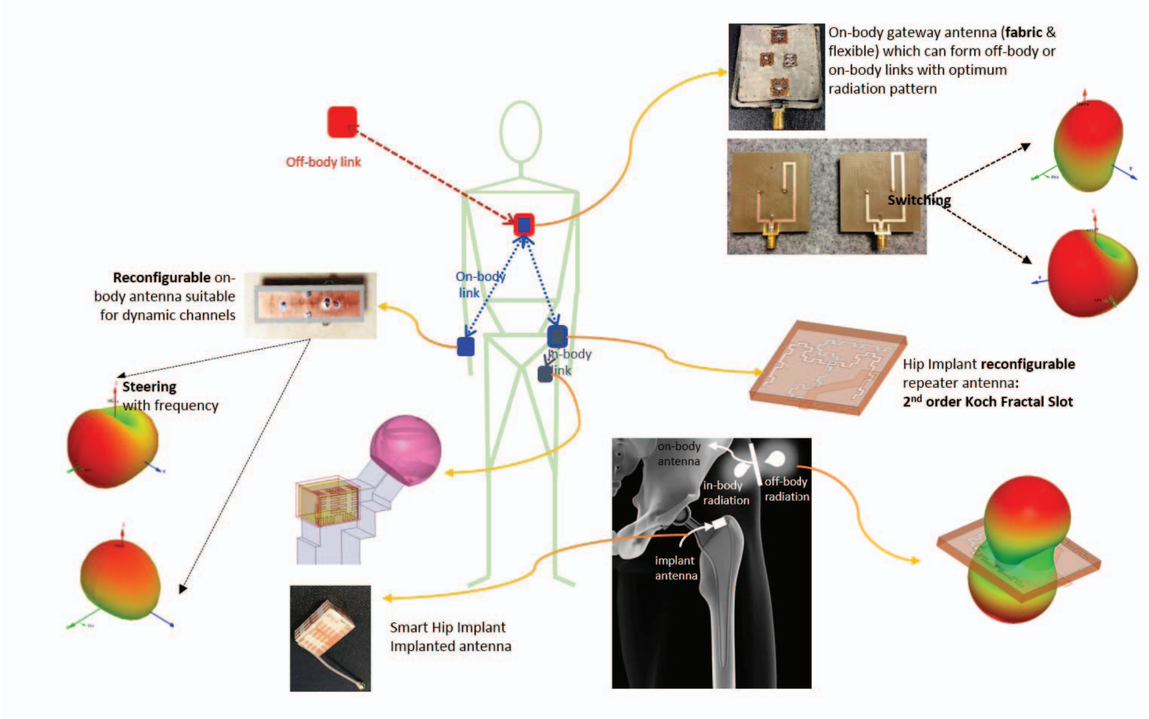

Fig. 2. Proposed wearable antennas presented at system level

IV. Conclusion

A system level approach to the wireless network of wearable sensors was discussed in a future scenario where a person wears multiple non-invasive devices which communicate between themselves, smart implants and off-body gateways. The common challenges for the design of such wearable antennas were highlighted and some antennas previously proposed by the author were reviewed. The antenna re-configurability was emphasized to achieve higher link quality for various types of connections and longer battery life.

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