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Rigorous Analysis and Evaluation of Specific Absorption Rate (SAR) for Mobile Multimedia Healthcare

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ABSTRACT The application of wireless body area network (WBAN) in health sector is crucial. It prolongs the life expectancy and improves the quality of life by enabling remote health monitoring. Despite many advantages, it may result and exacerbates various extant health issues especially in the context of mobile multimedia. Due to high data rate of mobile multimedia applications, heat generated from sensor devices is considerably high and results in thermal dissipation. The thermal impact of sensors on human body has largely been a neglected topic. The paper rigorously analyzes the specific absorption rate (SAR) impact on human body. Moreover, the paper largely contributes by comprehensively evaluating SAR impact under various circumstances and dependency factors. The analysis and evaluation show promising results that can significantly help the successful design and deployment of WBAN strategies. The paper also provides great guidance to numerous practitioners of this domain.

INDEX TERMS Wireless body area network (WBAN), specific absorption rate (SAR), mobile multimedia, Internet of Things (IoTs), smart healthcare.

I. INTRODUCTION

The use of Internet of Things (IoT) and mobile multimedia services and applications in health care are the most demanding solutions. For this purpose, IoT uses communication networks comprise of sensor nodes built for a variety of medical applications; for example, collecting and examining a person's vital signs (like heart rhythm, blood pressure, oxygen and temperature), multimedia data (like x-ray, MRI, CT-scan, EEG and EMG) and fitness information or human activities for medical purpose. Hence, the application areas of WBAN may include ubiquitous health care specially for elderly and disable people, sports, military and entertainment. Therefore, Wireless Body Area Network (WBAN) is one of the most suitable technologies to use IoT and multimedia mobile devices in health sector [1] like monitoring heart diseases [2]. Fig. 1 shows a typical Mobile Multimedia for health care Using IoT.

WBAN consists of sensor nodes that can be either placed on human skin or implanted within body tissues [3]. It has recently become a focus of research on variety of mobile multimedia applications especially for health care sector as it facilitates continuous monitoring of health condition of patients in timely and effective manner [4], [5]. The human body is a lossy medium where the electrical signals are absorbed by the surrounding tissues [6]. The result is highly attenuated signals and increase in temperature of tissues.

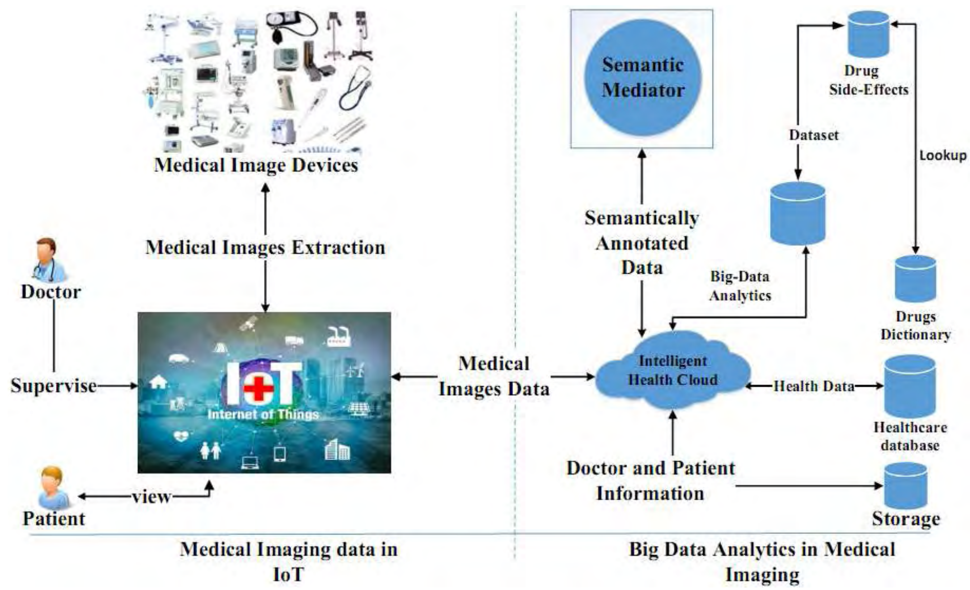


FIGURE 1. Mobile multimedia for health care using IoT.

This poses serious health risks and must be avoided. The nodes that are farther from the central node have to increase their transmitting power to overcome packet loss. If an organ in body receives electromagnetic signals for longer time period as it does in mobile multimedia application for healthcare, then it will be affected from heat generated by nodes and might be injured or damaged. In other words, the more data generated by nodes (as in the case of mobile multimedia), the more would be the chance of tissue damage. Specific Absorption Rate (SAR) is defined as the amount of radio frequency energy absorbed by human tissue [7]. Higher SAR level means more electromagnetic signals absorbed by the body and more harm to the health [8]. Hence, thermal impact of sensors on body is a critical issue in mobile multimedia for health care that needs to be addressed.

In this paper, a detailed analysis of SAR is presented. As discussed earlier that SAR has a profound effect on human health. Hence, it is desirable to maintain the value of SAR within a threshold level. This can be achieved through different ways like use of thermal aware routing protocol to avoid heated nodes in a routing path.

The main contributions of this paper with respect to the current state-of-the-art are manifold:

- Rigorous analysis of SAR impact on human body in mobile multimedia applications for health care
- Comprehensive evaluation of SAR under various conditions
- A thorough study on a largely neglected topic in mobile multimedia for health care
- Promising results may help to design and deploy efficient WBAN strategies
- Provides a roadmap for researchers as well as for practitioners of the domain

The paper is organized as follows: Section 2 describes the related work. Safety aspects are presented in Section 3. A brief description of SAR is presented in Section 4. Results and discussion are presented in Section 5. Finally, Section 6 concludes the paper.

II. RELATED WORK

The wide explosion in usage of mobile multimedia applications for health care has paved way for many researchers to study its performance in terms of packet success rate, error free delivery and network longevity [9], [10]. Chandran *et al.* [11] proposed an android based mobile multimedia application for health care named Digital Medicine. Peddi *et al.* [12] proposed a cloud-based mobile e-health calorie system. The system can categorize eatable items in a dish and then process for each food item the complete calorie with high accuracy. The most important challenges in the field of mobile multimedia health care are to determine human behavior in the social area in real time [13] and handling the Interoperability [14], [15] of IoT devices due to its high level of heterogeneity.

Few investigations have been made to study the impact of SAR on human body [16]–[18]. Some of the research experimented with physical design of antenna or the node itself to study the effect of EMF radiations on human tissue. Tuovinen *et al.* [19] examined different input powers that can be fed to UWB antennas to study the effect of SAR on human tissues. 3D electromagnetic (EM) simulation software that utilizes finite integration technique (FIT) has been used to calculate input powers of two different antennas. This experiment calculated the maximum amount of power for these antennas that crosses the SAR limits provided by IEEE [20] which causes the tissues to heat up. It was also observed that temperature rise is more significant in tissues with higher water content e.g. muscles and skin than fat. These findings are helpful in determining the suitable positions of different sensor nodes on different parts of body. Gil and Fernndez-Garca [21] compared two antenna designs i.e. wearable patch antenna and PIFA antenna and studied their impact on SAR on human trunk. The simulation results showed that due to homogeneous ground plane design of patch antenna, SAR levels were under regulation levels thus preventing back radiation effect. However, high area is required for patch as compared to microstrip element. On the other hand, the PIFA antenna resulted in higher back radiation presenting higher SAR values. Furthermore, different scenarios regarding space between antenna and patch were observed. By distancing the antenna at 1 cm, the SAR values met the criteria in case of PIFA. By placing both antenna types at 2 cm, both cases satisfied the SAR legal requirements which increased the wearer's comfort as the contact of skin and copper was minimized.

During packet transmission, the EMF radiation of sensor node correlates with power and distance of sensor nodes. If the distance is larger between sensor nodes and coordinator, higher power is required for antenna to ensure packet delivery. Higher transmit power will lead to increase in temperature causing the SAR level to exceed its limit.

Reducing the impact of SAR is still a challenge which requires innovations in physical design of WAN nodes along with improvements in MAC and routing layer to ensure maximum performance and user's comfort.

The sensor nodes in WBAN are divided into wearable and implanted nodes. The impact of SAR on human body regarding the implantable nodes has not been extensively studied.

The effect on SAR based on transmission performance of wireless endoscope has been investigated in [22]. Due to small size of endoscope node, the SAR will be highly localized as wireless communication depends on transmit power. The author used FDTD (Finite Division Time Domain) simulations to obtain appropriate transmit power for reliable data transfer. The simulations were performed on numerical human models and transmit powers were obtained that ensured less bit error rate. The results showed that the SAR value did not exceed the safety guidelines when these transmission powers were used for the endoscope device.

According to [8], if the relay nodes are placed in optimal position for sensor nodes to communicate to the hub via these relay nodes, high success packet delivery rate can be achieved and negative impact of SAR can be minimized. The authors used Particle Swarm Optimization (PSO) to calculate the optimal position for relay nodes in the body. The addition of relay nodes ensured improved packet success rate and optimal placements of these relay nodes decreased the negative impact of EMF on body thus significantly lowering the SAR level.

III. SAFETY ASPECTS IN MOBILE MULTIMEDIA FOR HEALTHCARE

In mobile multimedia applications for healthcare, various types of medical sensor devices are implanted in human body through surgery or put around the body in clothing to monitor patient's medical activities. These devices communicate multimedia contents like clinical audio-visual notes with each other or with the remote server nearby. On one hand, these devices will help the patient to convey the critical abnormal values to the health care center but on the other hand, the transmission and reception of multimedia contents in the form of high frequency electromagnetic signals may harm internal tissues of human body due to exposure to radio waves. This kind of danger to human health is termed as radiation exposure. The sources of radiations include X-rays, electrocardiography (ECG), electromyography (EMG), electroencephalography (EEG) etc. Passing electric current or electromagnetic radiations through human body has many dangers, thats why various regulatory bodies established all over the world to make laws, policies and standards to assist safety of human. In this regard, a standard IEC 60601 was introduced in 1977 for safety of medical electrical and mechanical devices/equipments [23]. Key safety features of human body, which are listed in [24] and [25], are described in detail in the following subsections.

A. OPERATIONAL AND SOFTWARE CONCERN

Safety of health from all types of hazards in the environment is fundamental human right and is a pre-requisite for refining of human health [26]. The operational aspect of safety reflects that medical devices must be correctly calibrated and utilized to save patient from any kind of danger. Although many medical devices are hardware-based and are operated mechanically or electrically but their operation is controlled using some software. Therefore, it is necessary that the device software must be error free to avoid any harm to the patient.

B. RADIATION ASPECT

It is possible that many tiny devices are implanted inside patient's body. These devices can be placed around the body in clothing to transmit various information regarding different abnormalities in body to external wireless network. These information are propagated in the form of electromagnetic (EM) waves which may be harmful to the patients depending upon the intensity of radiations and duration of exposure. It is recommended to keep these radiations in limit to maintain good health and safety of patients.

C. BIO-COMPATIBILITY OF DEVICES

Medical devices are manufactured from several physical components each having unique physical and chemical properties. These devices, when come in contact with the patient's body, may have adverse impact on patient's body depending

TABLE 1. Simulation parameters.

Parameters	Values
No. of nodes	12
RSSI Range	-100dBm to 0dBm
Receiver Sensitivity	-90dBm
Transmission Power Levels	[-25, -20, -15, -12, -10, -5, -3, 0]dBm
RSSI at a Reference Distance (1m)	[-76 -54 -45 -45 -42 -39 -32 -27]dBm
Energy Consumption (mJoules)	[14.8629 14.73303 14.54544 14.35785 14.15583 13.96824 13.78065 13.57863]mJ
Thermal Threshold	0.34 W/Kg
Path Loss Exponent, n	2.4
Reference Distance, d_0	1 m
Initial Energy, E_s	160 mAHr
Data Rate	250Kbps
Carrier Frequency	2.4GHz

upon their sensitivity to external entities. Therefore, compatibility of the devices with the patient's body is essential for the safety of the patients.

D. MECHANICAL STRESS

The mechanical safety aspect is related to sudden accidents like post traumatic shock that arise from mechanical stress. It is necessary to ensure the patient's safety during implantation of sensors within a body or using medical devices like infusion pump [26].

E. ELECTRICAL CURRENT

This safety aspect emphasizes on the insulation of electrical conductor inside or outside the medical electrical equipment so that there is no direct contact of the conductor with the patient. The purpose is to keep protected the patient from electrical shock.

IV. SPECIFIC ABSORPTION RATE (SAR)

Specific Absorbtion Rate (SAR) is a way to measure the level of radiation being absorbed by a human body. Its unit is in Watts per Kilogram (W/kg) or milliWatts per gram (mW/g). It is the rate of absorption by human tissue per unit weight. It is given by [27]

$$\mathrm{SAR} = \frac{\sigma |\mathrm{EF}|^2}{\rho} \tag{1}$$

where EF is the induced electric field, ρ is the density of the tissue, and σ is the electrical conductivity of the tissue. SAR is the power dissipation per unit mass of tissue. In the head or chest, acquaintance for 900 seconds to 8W/Kg SAR in a gram of tissue may have a substantial risk of tissue damage [23]. Sensitive organs due to a dearth of blood flow are likely to thermal impairment (e.g., lens cataracts [28]). It is a bit of high concern regarding exposing an eye to a Wireless LAN [29] or Infrared [30] radiation.

Each node has a dipole antenna of length dl. The SAR is due to the radiations emitted from the antenna. In order to measure SAR, the near field region is considered around the antenna which is at most d_0 distance from antenna $d_0 = \frac{\lambda}{2\pi}$. Here, λ is the RF wavelength for wireless communication. SAR is given by [31]

$$SAR = \frac{\sigma \mu \omega}{\rho \sqrt{\sigma^2 + \epsilon^2 \omega^2}} \left(\frac{\mathrm{Idl} \sin\theta \exp^{-\alpha \Re}}{4\pi} \left(\frac{1}{\Re^2} + \frac{|\gamma|}{\Re} \right) \right)^2 \tag{2}$$

where σ is the body temperature conductivity which is 1.79 $\frac{S}{m}$, μ is the permeability which is $4\pi \times 10^7 \frac{H}{m}$, ω is the frequency band, ρ is the density of tissue which is 1040 $\frac{Kg}{m^3}$, ϵ is the relative permittivity which is $52.73 \frac{F}{m}$ at 2.4 GHz, I is the current drawn at a particular power level of radio, dl is the length of antenna which is 1 m in length, $\Re$ is the distance from the source to the observation point, γ is the propagation constant and θ is the angle between the observation point and the xy plane. Here, the antenna is assumed to be perpendicular to XY plane; thus, we take $\sin\theta = 0$.

The attenuation constant α in $\frac{Neper}{m}$ is given by

$$\alpha = \omega \sqrt{\frac{\mu \epsilon}{2}} \left[\sqrt{1 + \left(\frac{\sigma}{\omega \epsilon} \right)^2} - 1 \right]^{\frac{1}{2}} \tag{3}$$

The typical values of all the parameters discussed above is at room temperature ($25°C$) and body temperature ($37°C$).

V. RESULTS AND DISCUSSION

A. SIMULATION SETUP

In the simulation, 12 implantable nodes are deployed at different body parts. The wireless link between the transmitter and receiver nodes depends upon the state of a body and may be degraded due to postural changes. The initial energy of each sensor node is 160 mAHr. The transmission power level of each node ranges from 0dBm to -25dBm. Table 1 shows the simulation parameters. These extensive simulations analyze the SAR from different aspects. More specifically, the relationship of SAR with distance, current drawn, TPL, RSSI and position of the sink have been analyzed and discussed in the following sections.

B. ANALYZING SAR ON THE BASIS OF CURRENT DRAWN AND DISTANCE

As discussed earlier, a high value of SAR may result in sensitive tissue damage. Therefore, it must be considered while developing a routing strategy. In general. SAR depends upon two factors:

1) Distance from source point to observation point
2) Current provided to Antenna

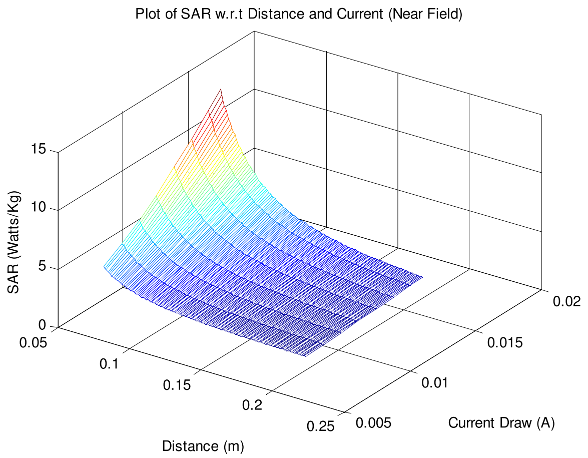


FIGURE 2. SAR with respect to distance and current.

In Fig. 2, impact of current draw and distance on SAR can be seen together in three different scenarios:

1) Distance remains constant; Current provided to Antenna varies
2) Current provided to Antenna remains constant; Distance from source point to observation point varies
3) Both factors vary

SAR is observed at an observation point in the near field as well as far field regions. These two types of regions are around the transceiver antenna and is based on the distance from antenna to a point of observation. It can be clearly concluded from the figure that in the near field, the value of SAR is higher than the case of far field region. SAR is heavily dependent on the current provided to the antenna or in other words, high transmission power results in high value of SAR. The distance from source point to observation point is kept constant. Distance between the antenna to a point of observation has a high impact on the value of SAR. The more is the distance between source point and observation point, the less will be the value of SAR.

C. SAR WITH RESPECT TO SINK POSITION

Sink is the node where data is collected from all the sensor nodes. Various sink placement strategies like RSP, GSP, ISP and GASP have been proposed along with a discussion of its pros and cons [32]. None of the existing approaches considered SAR as a parameter for the sink placement.

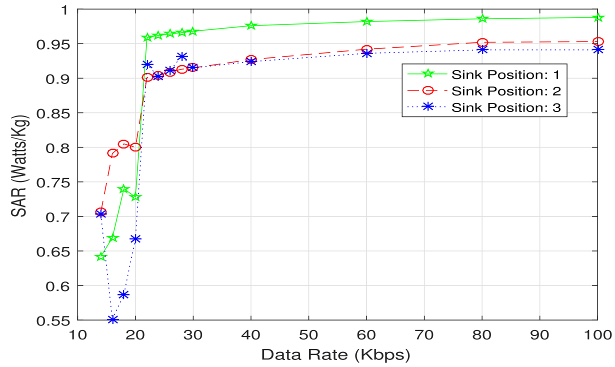


FIGURE 3. SAR with respect to sink position.

The sink should be placed in such a manner considering the SAR value. Moreover, the data rate is proportional to the SAR. The more is the data rate, the more will be the value of SAR. Fig. 3 shows the SAR plot with respect to three different sink positions. It is clear from the plot that the position of the sink with data rate matters. Therefore, placement of the sink at the right position with optimum data rate to decrease SAR is desirable. This is because data from all the nodes are collected at the sink. If the sink is located at a place where the nodes are densely populated, SAR is going to be increased; however, at places where nodes are not densely populated, the sink can be placed over there to reduce SAR.

D. SAR OF INDIVIDUAL NODES

Fig. 4 shows SAR of different nodes. These values are dependent on number of neighbors of a node. The more neighbors a node has, the more is its SAR value. In the Fig. 4, node 1 is a node which has least number of neighbors, therefore, its SAR value is much lesser than other nodes.

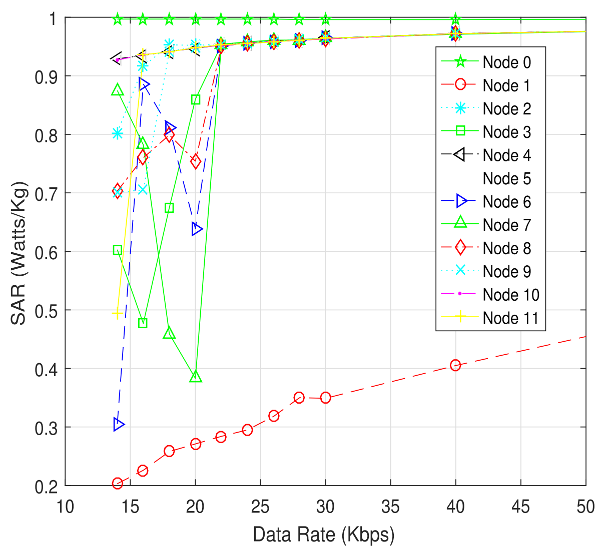
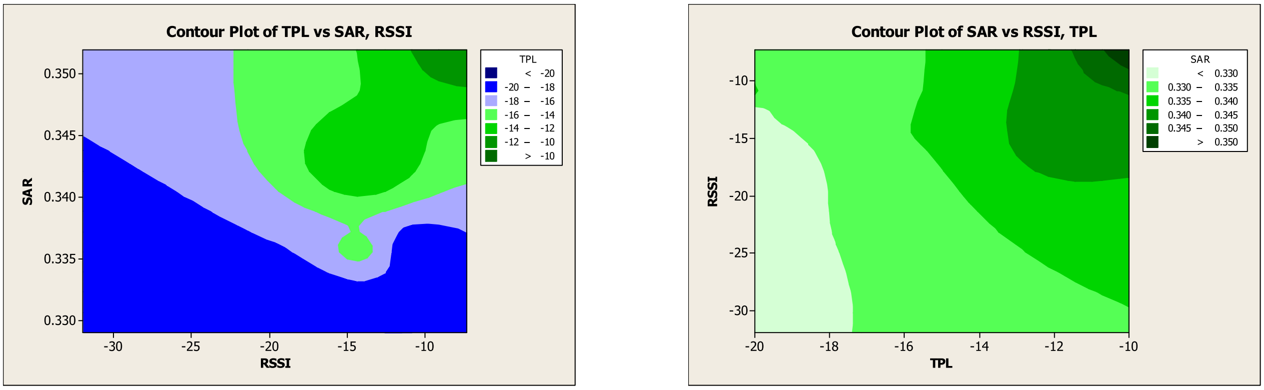
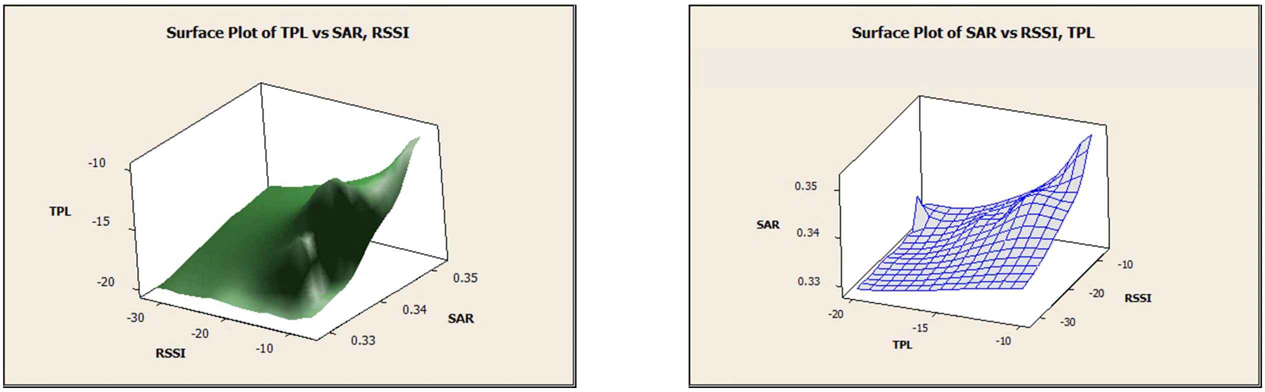


FIGURE 4. SAR per node.



(a) (b)

FIGURE 5. Relationship among SAR, TPL and RSSI using contour plots.



(a) (b)

FIGURE 6. Relationship among SAR, TPL and RSSI using surf plots.

E. TPL, SAR AND RSSI

Tuning Transmission Power Level (TPL) while achieving reliability at the same time is an important aspect of WBAN. Most of the routing protocols use maximum transmission power level to ensure reliability. However, it results in high interference and unnecessary wastage of energy resources. There are routing strategies that use transmission power control mechanism to ensure maximum energy saving and cares about tissue damage issue as well. This is done by selecting those nodes in a routing path where power dissipation is not too high. More power dissipation means more chances of the tissue damage. Hence, TPL strategy is used to save energy consumption. This approach also results in reducing SAR. The reason is that using low TPL results in low Received Signal Strength Indicator (RSSI) which is a metric for measuring the signal strength.

Fig. 5 shows the potential relationship among SAR, TPL and RSSI by using contour plot. It display the 3-dimensional relationship of SAR, TPL and RSSI in two dimensions, with x- and y-factors (predictors) plotted on the x- and y-scales and response values represented by contours. It is like a topographical map in which x, y and z-values are plotted instead of longitude, latitude, and elevation. The figure shows how TPL and RSSI affect the SAR (contour). It is clear from the figure that there is a high dependency of SAR and TPL on RSSI. The low TPL results in low RSSI which in turn leads to low SAR.

Figure 6 is another representation to explore the potential relationship among SAR, TPL and RSSI. The predictor variables are displayed on the x and y scales, and the response (z) variable is represented by a smooth surface (3D surface plot in Figure 6(a)) and a grid (3D wire frame plot in Figure 6(b)). The figure concludes that high TPL results in high RSSI and thus, high SAR. However, low TPL does not always results in low RSSI.

F. SUMMARY OF SAR ANALYSIS

Fig. 7 summarizes the SAR pattern. Anderson-Darling normality test has been performed in order to assess whether SAR pattern comes from a specified distribution. Here, A is one of the best empirical distribution function statistics for detecting most departures from normality. Since A^2 exceeds a given critical value, therefore, the hypothesis of normality is rejected with some significance level. 95% confidence interval for mean, median and standard deviation is also given.

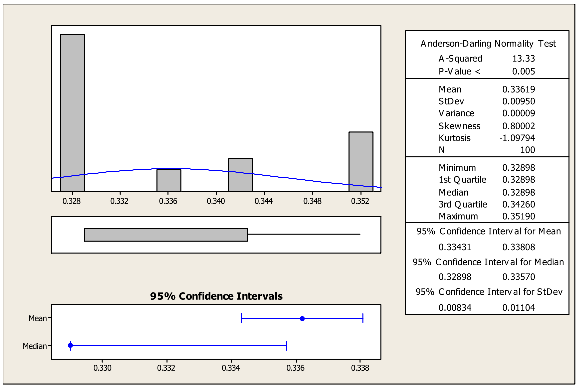


FIGURE 7. SAR summary analysis.

VI. WBAN CHALLENGES

The major developments in miniaturized, high performance sensor nodes have huge impact on WBAN applications especially in health care sector. These recent advances face many challenges, i.e. energy efficiency, thermal issues, increase in network lifetime and robustness etc.

One of the most critical challenges in WBAN is energy efficiency. Due to the application of WBAN in healthcare, the sensor nodes are required to be placed on or inside the human body. Thus, the size of the sensor nodes need to be small, taking into considerations the health protocols. The major module of a sensor node is the battery which should also be kept small keeping in mind the form factor of the sensor node. Ideally, the users are required to wear the nodes for longer time periods. But the size of the sensor node severely limits the size of the battery. Hence, efficient protocols are required to enhance the battery life as it is impractical and health hazard to replace the battery especially of implantable sensor nodes. Various energy harvesting techniques have been proposed and developed to harness energy from ambient energy sources [33], such as thermal energy produced by body is converted into electrical form to charge the battery, thus, eliminating the need to replace the battery.

The idle listening, overhearing and collision result in wastage of resources and ultimately degrade the performance of overall network. A node is in idle listening state when it listens for nothing. A node is overhearing when it listens for irrelevant packets. Listening is an expensive operation in terms of energy consumption and must be avoided at all costs [5]. Currently, several schemes are present to tackle these issues. The contention based MAC protocols such as CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) where nodes compete for channel before transmitting and TDMA (Time Division Multiple Access) where the nodes are assigned time slots and can only transmit in that specific time window [34] eliminate collision, overhearing and idle listening and are used in energy efficient MAC protocols [35].

The human body is a lossy medium where the electrical signals are absorbed by the surrounding tissues [6]. This results in highly attenuated signals and increase in temperature of tissues. This poses serious health risks and must be avoided. The nodes that are farther from the central node have to increase their transmitting power to overcome packet loss. Several thermal aware routing protocols have been proposed where mechanisms like power scheduling and traffic control are used to reduce overheating of body tissues [5]. In Thermal Aware Routing Algorithm (TARA), if a node's temperature reaches a certain threshold, it will no longer be used as a relay node and the traffic will be rerouted through alternate path [5].

When a body posture changes, it causes frequent topology changes as well. Body movements create dynamic environment which affects the density and topology of nodes in the network. It also affects the quality of links between sensor nodes and the central node/coordinator [36]. Thus, one of the challenges for WBAN is to achieve robustness against these topological changes [5].

Even though WBAN will provide major improvements in health care applications, various challenges remain in this area that need to be addressed. Many schemes have been proposed to solve these issues but there is always room for improvements.

VII. CONCLUSION

Mobile multimedia applications transfer multimedia data and generate huge amount of data. Due to the high data rate, heat generated from sensor devices is considerably high and results in thermal dissipation. This heat generated from nodes may result in sensitive tissue damage. Hence, to avoid any damage to body organs there is a need to analyze SAR. In this paper, an extensive analysis of SAR is provided. Moreover, a comprehensive overview of safety aspects and challenges is also elaborated. As discussed earlier, the tissues of a human body are sensitive to heat. Therefore, thermal impact of IoT devices must be considered while designing WBAN solutions in order to mitigate the risk of tissue damage. SAR is affected by varioes factors like change in the distance between nodes and the current provided to nodes' antenna. The position of the sink is also an important parameter for SAR. In this paper, all these aspects are evaluated rigorously.

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