A Scheduling Scheme for Efficient Wireless Charging of Sensor Nodes in WBAN

Md Khurram Monir Rabby[a,*], Mohammad Shah Alam[a,†] and Mohammad A Hoque[b,‡]
[a]Institute of Information and Communication Technology, BUET, Bangladesh
[b]Department of Computing, East Tennessee State University, USA
*khurram.rabby@gmail.com, †smalam@iict.buet.ac.bd, ‡hoquem@etsu.edu

***Abstract*—This paper presents a scheduling algorithm for point to point wireless power transfer system (WPTS) to sensor nodes of wireless body area networks (WBAN). Since the sensors of wireless body area networks are continuously monitoring and sending data to remote central unit, power crisis for these sensor nodes degrades the data transfer of patient monitoring system. Although energy harvesting from ambient sources using electro-magnetic induction enhances the longevity of sensor performance, continuous operation in the primary side decreases the overall efficiency. With such paradigm in sight, a framework is proposed for increasing the primary battery longevity and reducing the transmission loss, inductive power is transmitted from primary to secondary unit using medium access control (MAC) protocols for underlying the centralized scheduling opportunity in a collision-free scheme for channel access of rare yet critical emergency situation. In a preliminary study, the proposed scheduling for charging sensor nodes in a wireless body area network (WBAN) is evaluated in a case consideration.**

Keywords*—*wireless power transfer system (WPTS); wireless body area networks (WBAN); medium access control (MAC); energy harvesting (EH).

I. Introduction

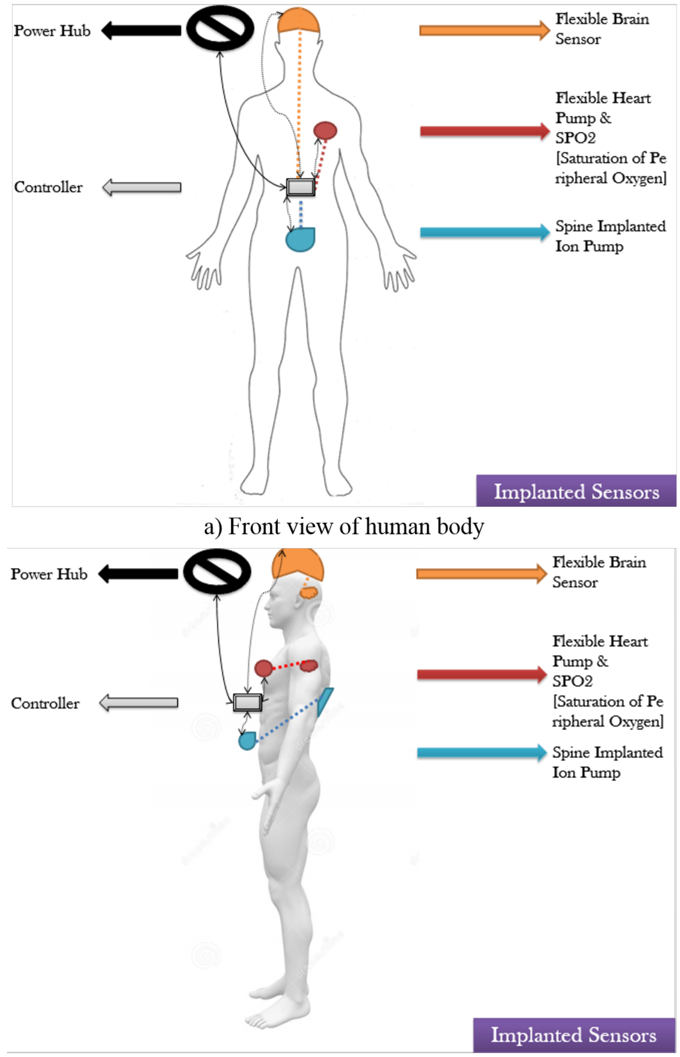
A recent technological achievement connected to health is possible due to the development in tiny, lightweight, wearable and ultra-low-power monitoring devices. Therefore, an integrated wireless body area network, so-called WBAN, is accomplished consisting of low-powered physical miniature sensor devices providing novel health monitoring opportunity for chronic diseases with wireless communication [1], [2]. In WBAN, embedded sensor nodes are transmitting environmental and physical data such as temperature, sound, or the presence of certain objects to the controlling unit under monitoring purpose [3]. The progress of wireless sensors come forth as new application in the medical market for the disadvantages of wired limitations such as: risk of infection, failure, patient discomfort and mobility [1]. On the other hand, essential instruments in Intensive Care Unit(ICU) such as heart rate monitors, pulse oximeters, spirometers and blood pressure monitors are coming forward to experience the wireless advancements of wearable devices which monitor blood pressure, blood glucose levels, heartbeat, sleeping patterns, etc. Another purpose of WBAN is to trigger reactive actions after collecting and collaborating of human body data since limited resources of on-body sensors fail to analyze the data they sense and so inappropriate drug dosage levels for a long time may prolong serious illness or even lead to death in some cases. Therefore, for the purpose of monitoring and controlling the dosage levels of drug infusion pumps and implanted defibrillator, on users body communicate with each other through wireless medium [2]. Although embedded wearable sensor nodes have multiple application in WBAN, they can only provide small and limited data transmitting and processing capabilities due to the battery powered sources. Moreover, energy losses due to the collision or corruption during broadcasting of packets, idle listening, overhearing of a node to receive some packets that are destined for other nodes, use of control packet overhead to setup data transmission and over emitting for energy waste caused by transmitting a message for unready nodes affect protocol design, sacrifice throughput, limited bandwidth usage and network lifetime through judicious usage of energy [4], [5]. In addition to that in-body battery monitoring and replacement cause to degraded networks efficiency [5]. To overcome the limitation of limited energy resources to facilitate health connected sensors, researchers have focused on intelligent duty cycling and energy saving techniques at all layers of the protocol stack, complex and non-ideal behavior of low-power wireless links, concurrent data transmissions, and the co-existence between wireless sensor nodes [4]. For multi sensor nodes, intelligent duty cycling makes it complex to be applicable in energy saving purposes. As an alternative, physical layer protocols are proposed to prolong the battery life time. Therefore, TDMA (Time Division Multiple Access), schedule or un-schedule based MAC protocols and hybrid schemes according to IEEE 82.15.4 are applied to use a super frame structure and guaranteed timeslot. These schemes have not been succeeded because of efficient slot availability and congestion in contention access period under intensive data exchanges [5], [6]. Recent technological development in energy harvesting (EH) of external electro-magnetic fields has become an area of active research for charging the implanted sources. That is why a comprehensive study of efficient EH application for WBANs is a challenging problem [7]. Sensors nodes for different driver mechanism are applied to meet the challenge although a comprehensive study of priority aware scheduling algorithm for on-demand wireless energy harvesting with satisfactory energy efficiency for implanted sensor nodes is yet to be proposed.

In this paper, we propose a scheduling scheme for charging embedded sensor nodes in WBAN. The proposed technique is applied in inductive wireless power transfer circuitry consisting of saturating class-C driver. In WBAN, since sensor nodes are placed very close to each other, power circuitry is chosen for small range as well as specific voltage and current rating. After designing the electronic link, the mentioned technique is implemented in primary circuitry for on demand based power requirement from secondary nodes. The cut-off voltage is maintained 10% of the nominal voltage to charge up the secondary nodes which main purpose is to transmit surrounding data to the controller unit. Therefore, controller circuit is the central monitoring device for analyzing voltage level data collected from different sensor nodes and give necessary instruction to the primary through MAC protocol to implement the scheduling process to maintain the nominal voltage rating. A test system is considered in a particular sensor node to verify the scheduling process for point to point dedicated wireless power transfer in WBAN where significant power improvement is observed. Simulation results are shown in comparison that single MOSFET oriented saturating class-C driver is more efficient than the existing double ones.

The rest of the paper is organized as follows. WBAN sensor nodes connected to inside human body through MAC protocol followed controller are discussed in section II. In section III, a step by step scheduling power transfer technique is presented. Inductive based saturating Class-C driver circuitry for charging sensor nodes is discussed in section IV. Simulation results as well as other analysis are done in section V. Finally, concluding comments are given in section VI.

II. System Modeling of Wireless Body Area Network

In a typical WBAN, embedded sensor nodes are required to be designed in such a way that wireless connection is possible to be communicated and also for charging purpose. To achieve this requirement, in body sensor nodes have been connected through a coordinator unit called controller. Since in-body sensors are significantly important to be wireless to provide flexibility of patient and also transmit from inside human body to outside controller parts for analyzing the transmitted data. This transmitted data has been divided into two parts. One part will carry the environmental and physical condition of the human body and the other parts will bear the information of voltage level from charge storage devices embedded in human body. In this analysis, in-body sensors are considered due to the complicity of energy to be transmitted to the embedded sensor nodes. Like typical sensor network, particular data from specific sensor nodes will always be a concern of the sender at certain interval of time. This time interval will be maintained by the controller unit. Moreover, since the controller unit can also monitor the power data, any degradation of voltage below threshold level will consider to be under the proposed scheduling scheme and trigger the associated circuit to start charging process according to the scheme. Significantly to avoid collision of data and power charging process different frequency level has been chosen to provide the flexibility of network level. In addition to that controller will provide the



a) Front view of human body

b) Side / lateral view of human body

Fig. 1: System Modeling of (WBAN).

data transmission scheme in a contention free Time Division Multiple Access (TDMA) protocol for minimum collision among the data transmission interval. The sample network modeling is shown in Fig. 1.

In Fig. 1 (a), it has been shown that three embedded sensor nodes are connected through controller by wireless link. The controller is powered by an external source called power hub through wire medium. In this analysis three embedded nodes i.e flexible brain sensor, heart pump and SPO2, and spline implanted ion pump are taken into account. From Fig. 1 (b), it has been seen that for each sensor there is a dedicated primary circuit situated just above the human body. The purpose of this dedicated primary circuit is to provide necessary inductive link to charge embedded secondary circuit to provide necessary power to the sensor nodes. The power source of primary circuit is considered battery because it is easy to replace from out-side human body and give flexibility to patient. All these primary circuits are connected to the controller unit via IEEE

802.15.4 protocol. However, for medical data analysis purpose secondary circuit is directly linked to the primary following contention free TDMA method.

III. SCHEDULING ALGORITHM FOR CHARGING SENSOR NODES

The main focus of scheduling technique is to charge embedded sensors before they reach below their threshold voltage level. According to IEEE, if the sensor required voltage is below the threshold level, the performance and data analyzing capability of the nodes will be degraded and so the performance and the transmitted sensed data may not be actual. Therefore, in the proposed technique threshold voltage level is considered as the boundary parameter below which the charging command will be triggered from the controller unit. In this case, if the time difference between voltage level below threshold level and the charge start up is more then there is the possibility to lose data which could lead to very much detrimental to the human health. Therefore, in this proposed technique to avoid transmission purpose delay in-body sensor nodes are sensed before six (6) cycles and minimum three (3) cycles are counted to consider any nodes under most immediate charging schedule process. On the other hand, at the same time data transmitting and sensor charging are possibility to interrupt one another. To overcome this difficulty different frequency level is maintained for the purpose of transmitting and charging requirement. Without emergency case consideration, data transmitting and charging are not followed in this proposed scheme. Most of the case, nodes are charged in their idle state. Taking into account of the above all conditions, the charging technique is proposed in algorithm.

Algorithm 1. Scheduling Algorithm for Wireless Charging Sensor Nodes in WBAN

If any $V_{sensornode} < V_{threshold}$ for next Six (6) cycles
  If any $V_{sensornode} < V_{threshold}$ for next three (3) cycles
    Start Charging process until nominal voltage level
  Else If sensor node is not in Idle State
    wait until t_{Data} transmitting period
    If sensor node is not in Idle State
      wait 2× t_{Data} transmitting until Sensor Node Idle
      If sensor node is not in Idle State
        Restart the process
      End If
    Else if $t_{nextDataarrival} > t_{charging}$
      Start Charging process until nominal voltage level
    Else
      Start Charging until nominal voltage level & sudden data arrival
      If sudden data arrival
        wait until $t_{Datatransmitting}$
        Restart the process
      End If
    End If
  End If
Else
  Discard the charging scheme
End If

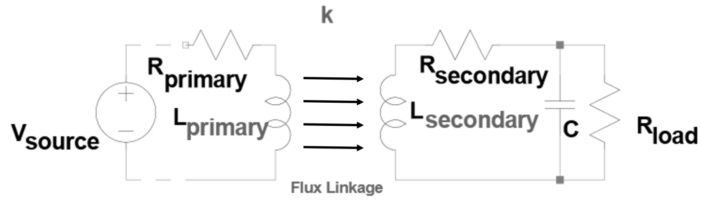


Fig. 2: Exact inductive link for non-resonant primary and parallel-resonant secondary).

From proposed algorithm, it has been shown that any node would be under charging cycle if its voltage level is calculated to be below threshold level. If its voltage condition maximum support upcoming (3) three cycles, then it would be charged directly as a priority based. Otherwise, depending on the node idle situation and next data arrival time schedule the sensor node would be charged up to the nominal voltage level.

IV. CIRCUIT MODELING

Electrical circuit is modeled for the purpose of implementing scheduling algorithm to make comparison in circuit level. The technique described in [8], [9] is followed to model the electrical circuit design. In this case, the steps are described below:

A. Link Modeling

In this circuit analysis, inductive links with a non-resonant primary and a parallel-resonant secondary are modeled. The optimization strategy is applied for the purpose of the system efficiency and the displacement tolerance by critical coupling. To calculate the equivalent impedance secondary parameters are calculated with respect to the primary side. In this case, coupling factor and load effect are considered to specify the loading range [8], [9].

From Fig. 2, it is found that due to change of current direction in the primary circuit flux linkage is observed from primary inductance, $L_{primary}$ to secondary inductance, $L_{secondary}$ for coupling factor, k to provide power to the load, R_{load} across the capacitance, C. Where, $R_{primary}$ and $R_{secondary}$ are placed to present the losses in the primary and secondary circuit respectively.

B. Saturating Class C Driver Circuit Modeling

The saturating Class-C driver circuit consists of a parallel L-C tank with a resistance to represent the parasitic and conductor losses in the circuit. Since the circuit is composed of L-C tank, there is always a circulating current present to convert from DC to AC [8].

From Fig. 3, it is seen that inductive tank coil, L_{driver} in saturating class-C driver circuit is tuned across the capacitor, C to couple fluxes according to the link requirement. Loss

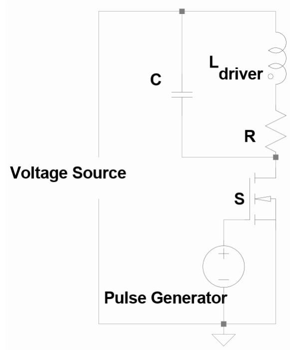


Fig. 3: Circuit diagram and operation of saturating class C primary coil driver.

is represented by resistance, R. For the switching purpose MOSFET, S is operated repetitively to maintain tank resonance frequency. This MOSFET is operated by a periodic pulse generator to maintain the rate of change of flux according to the secondary requirement.

C. Circuit Design for the Proposed Algorithm

The optimization procedure is followed to design the circuit for the proposed algorithm. According to this procedure, the major steps are described below:
Step 1: Geometry requirement calculation from power specification.
Step 2: Magnetic design to specify the range of parameters.
Step 3: Electronic design for primary and secondary circuit components selection.
Step 4: Switching the primary circuit according to the controller.

1) Magnetic Design: Following the procedure described in [8], the following parameters are selected in magnetic design procedure:

a) Primary and secondary coil: The coils specification is selected for the maximization of coil coupling and minimization of the losses according to the quality factor selected value. Coil dimension and shape are also identified through this technique [8].

b) Magnetic losses and frequency selection: Power and control frequency is selected in different range to avoid collusion for charging and data transmitting. Moreover, for charging purpose, minimum value of higher frequency is selected considering the human health, losses and radiation due to the eddy current. Other factors such as proximity and skin effect are ignored due to the less effect.

2) Electronic Circuit Design: Following the optimization procedure, the electronic circuit is designed according to the basic equation given in [9]. The parameters are selected within the range of magnetic designed link. If the parameters are calculated beyond the range of already specified value, then the whole process will be recursive again until all the value within boundary condition.

Since the circuit is implemented for scheduling algorithm to make the wireless power transfer system more efficient in less power consumption point of view by keeping the out-put within IEEE defined range, a MAC operated switch is established in the primary circuit. This MAC operated controller switch will be turned on when the out-put sensor node voltage sensed below the IEEE standard value.

The overall circuit is designed following the above condition shown in Fig. 4. In this design procedure, the following parameters are specified below:

Here, R_{load}: calculated load value from design specification, C_1: parallel tuned capacitor for primary coil, L_{s1}: primary coil for inductance, L_{s2}: secondary coil for flux linkage, R_1: primary circuit loss representation, C_2: filtering capacitor for noise and harmonic blocking, D: diode used for rectification purpose from AC to DC, C_3: voltage stabilizing capacitor across the load, R_2: secondary circuit loss representation, k: coupling factor, V_{pulse}: pulse generator for operating MOSFET as a switch and W: controller operated switch.

3) MOSFETs Configuration in Driver Circuit: Due to the limitation of BJTs as switching devices, power MOSFFETs are preferable to be operated for the same purpose. Depending on five parameters such as on resistance, voltage maximum, current handling capacity, transistor speed and gate driving source. MOSFETs are selected to be used as switches. However, the large gate capacitance of power MOSFET make it to be operated in parallel mode. Therefore, the existing technique uses power MOSFETs in parallel for saturating class-C driver circuit to handle large current [8].

The important parameter to select MOSFET is low drain to source voltage, v_{ds} and low on-resistance and current handling capacity. Therefore, startup in rush current is an important issue to be capable of maintaining design specified requirement. Taking all these points in consideration, from [8], it has been proved that if v_{ds} is at least 10 times greater than design required value, the MOSFET will be operated in higher efficiency. The benefit of this technique is that it not only increases current handling capacity but also rush current cannot do any damage during startup.

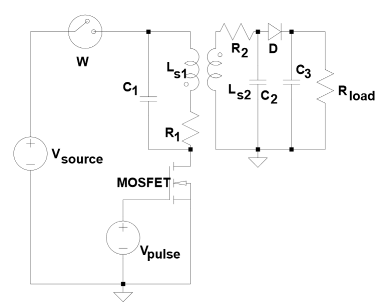


Fig. 4: Saturating class– C driver circuit design for inductive link with a parallel-resonant secondary.

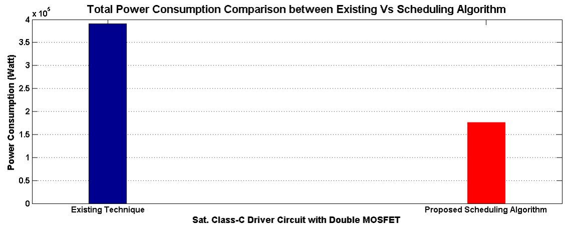


Fig. 5: Total power consumption comparison between existing and scheduling algorithm in sat. class-C driver circuit with double MOSFET.

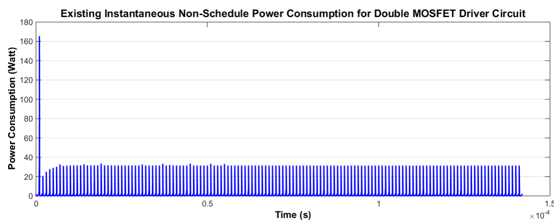


Fig. 6: Existing instantaneous non-schedule power consumption for double MOSFET driver circuit.

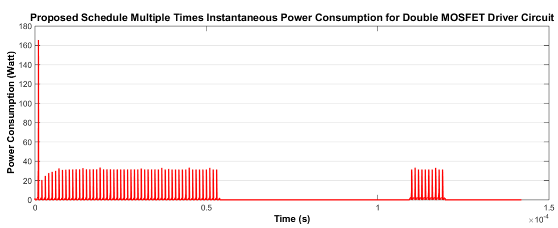


Fig. 7: Proposed schedule multiple times instantaneous power consumption for double MOSFET driver circuit.

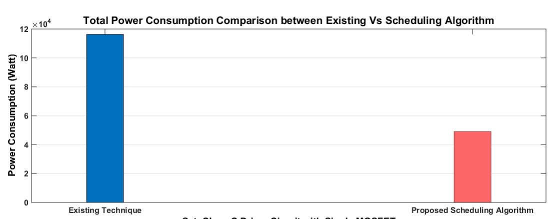


Fig. 8: Total power consumption comparison between existing and scheduling algorithm in sat. class-C driver circuit with single MOSFET.

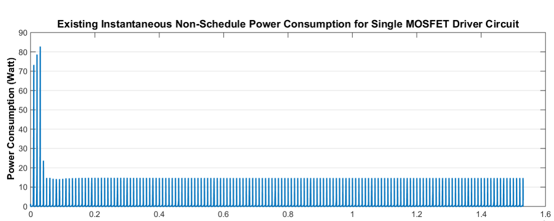


Fig. 9: Existing instantaneous non-schedule power consumption for single MOSFET driver circuit.

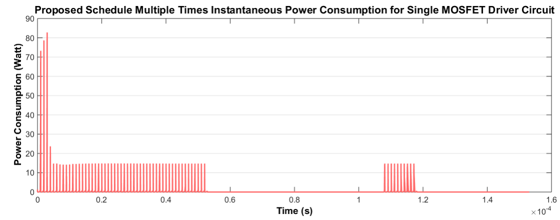


Fig. 10: Proposed schedule multiple times instantaneous power consumption for single MOSFET driver circuit.

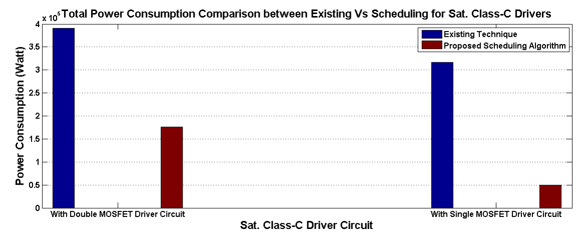


Fig. 11: Total power consumption comparison between existing vs scheduling algorithm for saturating class-C driver circuit with single and double MOSFET.

V. SIMULATION RESULTS AND DISCUSSION

In order to improve the performance of the wireless charging, proposed scheduling algorithm is implemented in a test small scale wireless power transfer circuit. For this purpose, the parametric value of the tested circuit is calculated using MATLAB as a simulation tool. Then, the proposed algorithm is verified upon two sample circuits consisting of saturating class-C driver with double MOSFET and single MOSFET configuration respectively. The overall circuits are simulated in SPICE simulator to collect data to analyze for the purpose of comparing power consumption difference after following scheduling algorithm in wireless power charging.

To be tested for the purpose of verification, the designed circuit is considered in a small wireless power range for body area network. Although MOSFET configuration is different in saturating class-C driver of primary circuit, the secondary load is considered as a telemetry unit of non-conductive housing placed around 70 mm deep inside human body. The sizing of telemetry in a non-conductive housing is capable of accepting a 6 mm solenoid with 20 mm diameter. The secondary embedded sensor is operating in a rated 4 mA maximum current from a 4 V-regulated supply. The value of circuit modeling parameters mentioned in Fig. 4 using the basic electromagnetic induction equation described in [9]. The calculated parametric values obtained following the circuit modeling is presented in Table I.

After setting the parametric value, the controller unit has provided necessary command through contention free TDMA based MAC protocol to maintain necessary operating rating for embedded sensor nodes using induction based wireless power transfer. For the purpose of analysis, the source of primary circuit has considered as 21.4 volt for the overall

TABLE I: Calculated Components Value Shown in Fig. 4 [8]

Parameter Name & Symbol	Value	Unit
Load resistance, R_{load}	1125	Ohm
Frequency, f	1	MHz
Coupling factor, k	0.71	%
Primary inductance, L_{S_1}	1.73	uH
Secondary inductance, L_{S_2}	1.73	uH
Primary L-C tuned capacitance, C_1	14.55	nF
Noise blocking capacitance, C_2	14.55	nF

circuit analysis for both saturating class-C driver circuit with the double MOSFET and single MOSFET. In this analysis, the proposed algorithm has been applied only a single node to make comparison with the existing one.

According to the existing criteria, the primary circuit has been kept on through the whole operating period for the purpose of the requirement. From the simulation result, it has been found that for 142 $usec$ operation purpose the total power consumption has been calculated 0.39053 MW for double MOSFET saturating class-C driver circuit. Meanwhile, for the same circuit after applying the proposed scheduling algorithm through controller unit, the total power consumption during the same period has been reduced to 0.17636 MW. The power requirement comparison has been shown in Fig. 5. In the explanation of power consumption reduction for the same performance, it has been proved through Fig. 6 and Fig. 7 time based instantaneous power consumption curves that scheduling algorithm has been operated to trigger primary circuit to provide flux to meet the load requirement if the secondary sensor node voltage has been sensed below 3.6 volt. Therefore, it has been noted from Fig. 7 that instantaneous power has been gone to zero for some interval of time during which secondary sensor node voltage has been in the range of 4 to 3.6 volt. From Fig. 6 and Fig. 7 it has been seen high spike during startup of transient period due to the inductive caused inrush current. Similar results but different output data has been found in saturating class-C with single MOSFET driver circuit. In this case, the total power consumption for existing technique and scheduling algorithm have been found 0.11626 MW and 0.049045 MW respectively for 153 $usec$ operation purpose shown in Fig. 8. It has also been seen from Fig. 9 and Fig. 10 that scheduling algorithm has operated primary less period of time than the existing one.

From Fig. 11 it has been observed after applying wireless charging proposed algorithm between same driver but different MOSFET configuration that saturating class-C driver circuit with single MOSFET consumes less power than double MOSFET orientation.

VI. Conclusion

In this paper, we presented an efficient scheduling algorithm for WPT in WBAN with saturating class-C driver. The advantage of this technique is proved by improving the efficiency for inductive wireless power transfer circuit by reducing consumption power in which single MOSFET has been used instead of two parallel MOSFETs in the driver circuit. Furthermore, from the performance comparison, it is observed that saturating class-C with single MOSFET is more energy consumption efficient for scheduling algorithm than the double MOSFET configuration. Although in this analysis it is assumed that primary circuit is battery powered devices, the flexibility on-body sensor devices make it feasible to be replaced after voltage drainage in a particular period of time. Since power consumption reduction in turn of improving efficiency is always an important issue for the above mentioned technique, scheduling among on-body and in-body sensors promise as a further improvement for WPT in WBAN.

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