Very-High-Throughput Millimeter-Wave System Oriented for Health Monitoring Applications

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Abstract **– Millimeter-wave transmission systems allow for very high throughput rates and broad bandwidths using wireless technology. Most Body Area Networks (BANs) work in the high MHz or few GHz range, which limit the channel capacity of the system. If the bandwidth is narrow, only low spectrally-efficient modulation techniques can be utilized. In this study an energy-efficient radio-over-fiber media access control protocol using the unlicensed 60-GHz millimeter-wave (mm-wave) band is proposed. The protocol can be best described as an algorithm that generates an isometric distribution of the available frequency-time resources and services the slave motes in monochromatic groups. The master mote builds a frequency-time two-dimensional grid that organizes the chronological service order of this FD-TDMA hybrid protocol. This mechanism provides a collision-free environment in which the sensors can achieve energy independence, also referred as self-sustainability in this work, which is an important feature in BANs. Results show that the proposed protocol successfully manages the BANs in a collision-free and energy self-sustainable manner.**

Keywords: 60 GHz, Area Network, BAN, Body, BSN, Collision-free, Energy Efficient, MAC, Millimeter, Protocol, Self-sustainability, Sensor Networks, Wireless.

I. INTRODUCTION

Wireless sensor communication networks (WSCNs), are becoming a ubiquitous system used in daily activities, such as health monitoring, security surveillance, and environmental monitoring. A health oriented network that detects erratic health conditions and monitors the immune-system stability and pathologic bodily manifestations are known as body sensor networks (BSN) or body area networks (BAN). Today most BANs work in the high MHz or few GHz frequency range and have a narrow channel, in some cases limited by government spectral allocations, which implies that the motes cannot operate with spectrally-efficient modulation techniques. These impairments are diminished at the mm-wave range, also known as the extremely high frequency (EHF) range. At these frequencies high bit rate transmissions can be achieved, even with low spectral-efficiency modulation. A spectral efficiency of 0.2 bps/Hz (typical value for OOK with an E_b/N_0 of 2dB using soft coherent detection) at 60 GHz can yield throughputs of over 10 Gbps. Some companies, such as VμbIQ, claim to successfully transmit using QPSK modulation at the 57 – 63 GHz range, which doubles the spectral efficiency. In the future, when BANs are capable of collecting high resolution information that will require large throughputs to be sent though the BAN and perhaps uploaded to a healthcare center, it will be necessary to upgrade to mm-wave technology.

Wireless communication systems operating around 60-GHz mm-wave have over 5–8 GHz of unlicensed bandwidth that can be exploited to achieve high-throughput wireless communication up to several tens of Gbps. Aggressive frequency reuse at 60-GHz mm-wave band can restrain ICI and adjacent channel leakage (ACL) [1], [2]. Today, the low cost and low power consumption 60-GHz transceiver (which can fabricated with 90 nm CMOS technology and occupy an area of several mm) makes it a feasible and integrated solution for short distance high data rate applications, especially for BAN.

In this work we propose a collision-free media access control protocol that can sustain power unlimitedly by efficient energy-aware scheduling. The proposed media access control protocol is described in section II. In section III, the results and simulations are presented; specifically, the power efficiency performance of various access methods such as Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), and Frequency Division-Time Division Multiple Access (FD-TDMA) are analyzed. Section VI presents the conclusions derived from this work, and finally section VII discusses the future work.

II. MEDIA ACCESS CONTROL PROTOCOL DESIGN

The media access control protocol is designed to serve a specific topology that consists of a remote antenna unit (RAU) that either communicates directly with the sensor motes (SMs) or it relays the information through a relay master (RM). A list of assumptions is necessary to define the model that leads to the final design of the protocol, and are as follows:

- SMs have fixed channel frequency and are unable to dynamically tune to a different frequency.
- SMs can connect or disconnect (e.g. fail) to the BAN at any time.
- All SM motes have the same clock speed than the RM and RAU.
- All SMs must have frequencies that fall within a grid of channels supported by the RM and RAU.
- The battery of the nodes cannot charge beyond the battery energy capacity, i.e. there is a fixed maximum.
- All nodes begin with fully charged batteries.
- The power consumption of the RM is dependent on the amount of time used and independent of the amount on channels used. The RM has a finite amplitude voltage capacity and many nodes can connect at a single frequency. To maintain the maximum amplitude each individual node transmitting in the same time slot can be scaled, thus the power will be independent of the number of nodes using the same time slot, but will be dependent on the time length of the slot.
- Energy change (increasing or decreasing) varies linearly with time. Depending on the energy source, the consumption or harvesting

power could vary with energy level, because this study does not target a specific energy source a linear behavior is assumed.

- There is no noise or interference. This is a MAC layer study and if information is lost due to noise or similar type of disturbance it is taken care of by the higher level layer protocols. The media access control layer is only concerned about connectivity and collision avoidance.

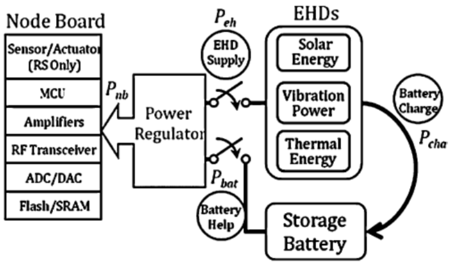


Fig. 1. Power management diagram of a node-board with a battery being supplemented by energy harvesting devices (EHDs).

A. *Power Management Mechanism*

The power dissipation of the networking activities in node board is defined as P_{nb}. To meet the need of energy-efficiency system design, energy gathered from external interactions, such as solar energy and vibration power, are delivered to network node based on Energy Harvesting Mechanism (EHM) for enhancing the system performance. Figure 1 illustrates the power operating principle of a wireless BAN where the Node-Board is powered by a battery and continuously extracting energy from EHDs (P_{eh}). If P_{eh} is lower than the consumed power volume of node board P_{nb} it means an additional power source is required to keep the node-board working, power stored in battery (P_{batt}) is loaded into node board for extra help. When P_{eh} is higher than P_{nb}, the surplus power (P_{cha}) is charging the storage battery unless the battery is already fully charged. A power regulator is used to switch among available power sources.

$$E_{net} = E_{harvested} - E_{consumed} \tag{1}$$

Self-sustainability condition:

$$E_{harvested} \geq E_{consumed} \quad or \quad E_{net} \geq 0 \tag{2}$$

$$E_{consumed} = \sum_{\Theta \in \, state} E^{\{\Theta\}} = E^{\{tx\}} + E^{\{rx\}} + E^{\{idle\}} + E^{\{sleep\}} \tag{3}$$

$$E = P \cdot T \tag{4}$$

$$E^{\{\Theta\}} = \sum_{c} \sum_{s} \left(P_{c,s}^{\{\Theta\}} \cdot T_{c,s}^{\{\Theta\}} \right); c \in channel, s \in slot \tag{5}$$

From assumption A8 and Equation (4) we get:

$$E^{\{\Theta\}} = \sum_{s} \left(P_{s}^{\{\Theta\}} \cdot T_{s}^{\{\Theta\}} \right) \tag{6}$$

$$P^{\{\Theta\}} = \sum_{s} \left(P_{s}^{\{\Theta\}} \right) \quad and \quad T^{\{\Theta\}} = \sum_{s} \left(T_{s}^{\{\Theta\}} \right) \tag{7}$$

$$E^{\{\Theta\}} = P^{\{\Theta\}} \cdot T^{\{\Theta\}} \tag{8}$$

If the energy harvesting rate is $P^{\{h\}}$ then:

$$E_{net} = P^{\{h\}} \cdot T^{\{h\}} - E^{\{tx\}} + E^{\{rx\}} + E^{\{idle\}} + E^{\{sleep\}} \tag{9}$$

Since harvesting is done at all times then:

$$\begin{aligned} E_{net} = & \left(P^{\{h\}} - P^{\{tx\}} \right) \cdot T^{\{tx\}} + \left(P^{\{h\}} - P^{\{rx\}} \right) \cdot T^{\{rx\}} \\ & + \left(P^{\{h\}} - P^{\{idle\}} \right) \cdot T^{\{idle\}} + \left(P^{\{h\}} - P^{\{sleep\}} \right) \cdot T^{\{sleep\}} \end{aligned} \tag{10}$$

The self-sustainability condition from (2) then becomes:

$$\begin{aligned} & \left(P^{\{h\}} - P^{\{tx\}} \right) \cdot T^{\{tx\}} + \left(P^{\{h\}} - P^{\{rx\}} \right) \cdot T^{\{rx\}} \\ & + \left(P^{\{h\}} - P^{\{idle\}} \right) \cdot T^{\{idle\}} + \left(P^{\{h\}} - P^{\{sleep\}} \right) \cdot T^{\{sleep\}} \geq 0 \end{aligned} \tag{11}$$

$$\begin{aligned} & \left(P^{\{h\}} - P^{\{sleep\}} \right) \cdot T^{\{sleep\}} \geq \left(P^{\{tx\}} - P^{\{h\}} \right) \cdot T^{\{tx\}} \\ & + \left(P^{\{rx\}} - P^{\{h\}} \right) \cdot T^{\{rx\}} + \left(P^{\{idle\}} - P^{\{h\}} \right) \cdot T^{\{idle\}} \end{aligned} \tag{12}$$

In terms of $T^{\{sleep\}}$ we have:

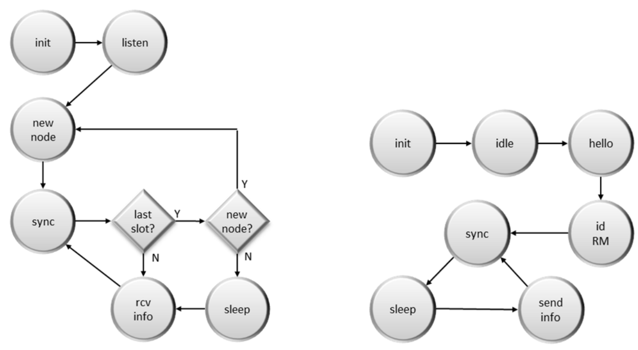
$$\begin{aligned} T^{\{sleep\}} \geq & \frac{\left(P^{\{tx\}} - P^{\{h\}} \right) \cdot T^{\{tx\}} + \left(P^{\{rx\}} - P^{\{h\}} \right) \cdot T^{\{rx\}}}{\left(P^{\{h\}} - P^{\{sleep\}} \right)} \\ & + \frac{\left(P^{\{idle\}} - P^{\{h\}} \right) \cdot T^{\{idle\}}}{\left(P^{\{h\}} - P^{\{sleep\}} \right)} \end{aligned} \tag{13}$$

This means we are able to have a self-sustainable node by selecting the appropriate value for $T^{\{sleep\}}$.

B. *Collision-free Media Access Control Protocol*

Many WSN MAC layer protocols rely on collision detection and network probing. This is inefficient resource usage, not only does it waist energy but it also wastes time. To avoid this, an RAU node can be introduced (if not already available) to organize and manage the SM nodes. By assigning time slots (TDMA) to nodes using the same frequency and allowing different frequency SMs to transmit simultaneously, the system can better utilize the available resources.

The RAU assigns each SM to a grid slot (described in more detail in the following section) and cycles through each time slot periodically. Only one SM can belong to a particular grid slot. After receiving the info from the last time slot it waits for a specific amount of time to allow for any new SMs to sync. The new SMs can only sync at this time, this allows the RM (if present) to sleep rather than having it in idle state the whole time the SMs are sleeping, just because there is a very small chance a new SM joins in. Because there is a small (but detectable) down time between transmit and receive states of the already linked nodes, the new SM has to wait for a predetermined amount of time to ensure the last time slot has passed to avoid unnecessary interference. If a new SM node is detected, then it is inserted into the grid and the new sync time is computed. Similarly, if an SM node is not transmitting at its assigned slot it is considered down and the grid is refreshed.



(a) (b)

Figure 2. State flowchart of the RAU (a) and SM (b).

The SM waits for the specified time to sync and sends a HELLO packet. Once it receives the ACK (which contains the sync time), the SM enters sleep mode until the sync time is reached. At that time the SM sends information and receives a new sync time. After processing the new sync time it goes back to sleep mode and continues the cycle.

C. TD-FDMA Assigment Grid

The FD-TDMA grid is a configurable matrix that dynamically adjusts to organize the SM nodes that are in the RAU's reach. Because FDMA is more energy efficient, the RAU arranges the SMs such that they occupy the least amount of time slots possible. The manner in which the channels and time slots are arranged in the matrix (rows and columns) is not important, but it is critical that once a standard is chosen the algorithm must follow this standard consistently throughout the code. In this work we chose the channels to be the rows and the time slots to be the columns, as shown in Figure 1.

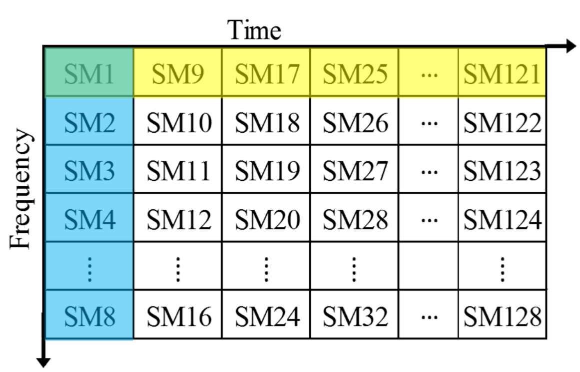


Figure 1. FD-TDMA slot grid.

The yellow portion is highlighting a single channel (one frequency), which is the same as TDMA, while the blue portion is highlighting the first time slot, same as FDMA. Having the grid is a hybrid of both multiple access techniques, which is a mechanism that provides and extra degree of freedom to arrange a larger group of nodes.

III. Simulations and Results

Simulations were performed in OPNET modeler 16.0. For all access techniques the nodes are placed in the exact same position. For all cases the starting time is a pseudo-random variable uniformly distributed between zero and five seconds. By pseudo-random it is meant that the selected starting times of each node will remain the same in every run and every simulation scenario as long as the seed of the random function is kept the same, which maintains all media access technique scenarios under the exact same conditions.

Table I. Simulation Parameters
System Setup (a) and Power Consumption (b)

Symbol	Description	Value
V_{cc}	System Supply Voltage	3 V
T_{sleep}	Time Length of Sleep Mode	25 – 1000 ms
T_{slot}	Time Length of Time Slot	1 ms
P_{eh}	Energy Harvesting Rate	100 μJ/s
B	Throughput	2.5 Gbps
E_{batt}	Battery Energy Capacity	5 J

(a)

Symbol	Current [mA]	Power [mW]
RM Sleep	0.02	0.06
SM Sleep	0.03	0.09*
Idle (Listening)	1	3
Receive	3.1	9.3
Transmit	3.3	9.9

*SM gathers info while it sleeps which is why it consumes more energy than the RM.

(b)

A. Sensor Mote

To obtain data for the SM a simple 1 RM and 1 SM architecture was used. Since adding SM nodes using the same frequency will add more slots (and the SM sleeps during this period). For this reason it is fair to use a single RM/SM pair to study the effects of the sleep period on the SM. Figure 2 shows the battery level of the SM at a specific time window. It can be observed that for T_{sleep} = 0.1 ms the time allowed for the sleep mode is not enough to recover the energy consumed. As for T_{sleep} = 1 ms, the harvesting device has enough time to charge the battery and supply energy to the SM.

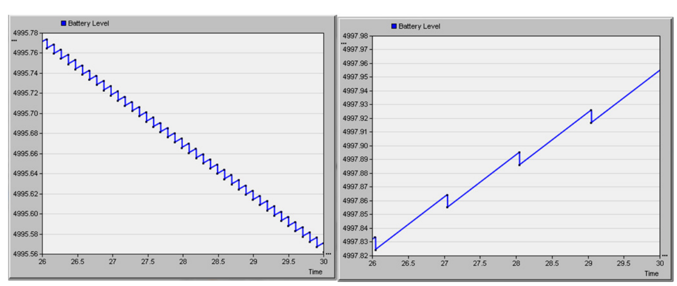


Figure 2. Time samples of the battery level of the SM (left) with T_{sleep} = 0.1 ms and (right) T_{sleep} = 1 ms.

The theoretical value of T_{sleep} can be obtained from Eq. (13) and Table I, which for one SM yields 882 ms. In the simulations (with a resolution of 10 ms) the SM was able to reach self-sustainability in the 860 – 870 ms range (see Figure 3). This gives a percent of error of less than 2.5%. Depending on the division multiple access technique used the results vary but to have a significant effect the slot time has to be considerably large. This occurs because the while the SMs in other time slots are transmitting the reference SM is in sleep mode. So depending on the multiple access technique used the SM remains in sleep mode for some extra time (in this particular case it is negligible time).

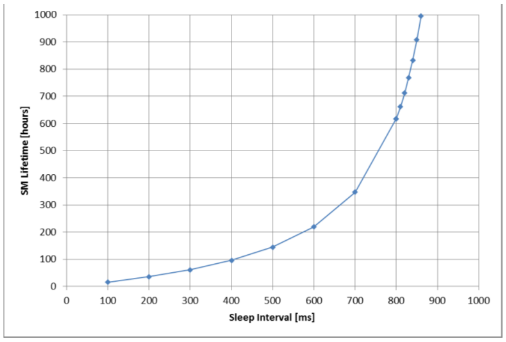


Figure 3. SM Lifetime versus sleep interval.

B. *Relay Master / Remote Antenna Unit*

For this scenario 4 SM are used. The channels of the SMs depend on the multiple access technique been simulated. For FDMA and TDMA the configuration is trivial, as the nodes are all in the same time slot (FDMA) or same channel (TDMA). In the FD-TDMA case, they form a 2x2 matrix occupying 2 channels and 2 time slots.

In this case the multiple access technique used will greatly affect the outcome of T_{sleep}. This occurs because the different access mechanisms have different time slot usage. In the FDMA case the RAU/RM only uses one time slot, while TDMA uses as many time slots as there are SM nodes. As mentioned in A8 (Section IV-B), the energy consumption only depends on the amount of time the antenna is in use. Similarly to the SM, the theoretical value of T_{sleep} can be obtained from Eq. (13) and Table I for the RM. The theoretical values for T_{sleep} for the different access techniques are: FDMA $T_{sleep} = 207$ ms, FD-TDMA $T_{sleep} = 414$ ms, and TDMA $T_{sleep} = 828$ ms. In the simulations the results were as follows: FDMA $T_{sleep} = 215 – 217.5$ ms, FD-TDMA $T_{sleep} = 430 – 435$ ms, and TDMA $T_{sleep} = 860 – 870$ ms, which coincidently to this resolution is the same as the SM. This gives a percent of error of less than 5.1% for all cases.

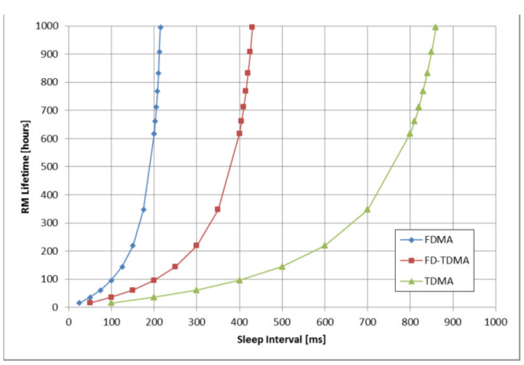


Figure 4. RM Lifetime versus sleep interval.

When energy self-sustainability is achieved the bit rate decreases. When the node is in normal sensing mode this is sufficient, if the BAN is required to transmit at full capacity the battery will be partially drained, but it can be recharged by returning into normal sensing mode.

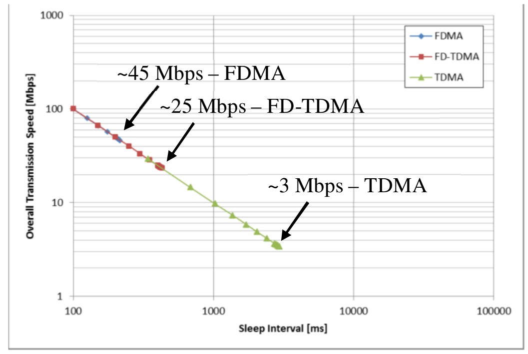


Figure 5. Effective throughput of the multiple access techniques.

IV. Conclusions

The media access control protocol proposed is oriented for millimeter wave wireless sensor network applications, such as health monitoring. The hybrid FD-TDMA media access control protocol has been proven in other work to be collision-free. The protocol proposed assigned the SM nodes in an energy-efficient manner into the frequency-time grid. It did this prioritizing the allocation of the SM nodes in the frequency slots; since the more time slots are occupied the greater will be the energy consumption. The proposed media access protocol also has a configurable sleep time duration variable, which can be dynamically or statically configured. This variable gives the protocol the ability to achieve self-sustainability if the nodes possess an energy harvesting device that can generate energy at a rate greater than the sleep mode consumption. The theoretical data presented is in high agreement with the simulation data. Results show that if the RM remains in sleep mode for ~215 – 430 ms in can achieve energy self-sustainability if it uses FDMA or FD-TDMA access control techniques, which is a required feature of BAN.

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