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Energy-Efficient Process-Stacking Multiplexing Access for 60-GHz mm-Wave Wireless Personal Area Networks

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Abstract—**Millimeter-wave technology shows high potential for future wireless personal area networks, reaching over 1 Gbps transmissions using simple modulation techniques. Current specifications consider dividing the spectrum into effortlessly separable spectrum ranges. These low requirements open a research area in time and space multiplexing techniques for millimeter-waves. In this work a process-stacking multiplexing access algorithm is designed for single channel operation. The concept is intuitive, but its implementation is not trivial. The key to stacking single channel events is to operate while simultaneously obtaining and handling a-posteriori time-frame information of scheduled events. This information is used to shift a global time pointer that the wireless access point manages and uses to synchronize all serviced nodes. The performance of the proposed multiplexing access technique is lower bounded by the performance of legacy TDMA and can significantly improve the effective throughput. Work is validated by simulation results.**

Keywords-60 GHz; access; MAC; millimeter; mm-wave; multiplexing; process-stacking; PSMA; WPAN

I. INTRODUCTION

Throughout history technologies have exhibited a logistic function growth pattern, commonly referred to as the technology s-curve. The s-curve is divided into innovation, improvement, maturity, and aging stages. In the wireless personal area network (WPAN) field, the current dominating technology is WiFi, which using a 2.4/5 GHz modulating frequency, channel widths of 20/40 MHz, MIMO antenna arrays, OFDM, and dense QAM constellations can reach 600 Mbps [1], indicating that this technology is reaching its maturity stages and it will become increasingly difficult to make significant improvements. For this reason millimeter-wave (mm-wave) technology is rapidly becoming the new alternative for WPAN. mm-Wave systems have already proven to transmit at 2.5 Gbps [2], using simple techniques. The 60 GHz frequency range is attractive to very-high-throughput applications found in research fields such as: WPANs [3][4] and e-Health [5].

Initial attempts to standardize the 60 GHz frequency range already exists. Among these standards is ECMA-387 [6]. One particular interest to our work is the band allocation of ECMA-387. It divides the operating frequency range (57.24 – 65.88 GHz) in four bands, as seen in Figure 1. Several motives for having a low number of bands exist, such as: low Q-factor filter design, less expensive, low number of users per picocell, etc. For this reason the focus of this work, same as other [7], is to design a time-domain multiplexing technique with efficient time-allocating capabilities. In this work a time multiplexing technique, called here process-stacking multiplexing access (PSMA), is proposed that has a process-stacking algorithm with a cyclic recharging process that is scheduled without altering the protocol behavior. Its versatility expands the packet-allocation-time reservation of TDMA to a diverse-process-time reservation ideology. This allows an easy incorporation of any process that needs to reserve access.

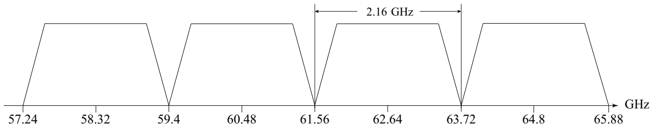

Figure 1. ECMA-387 operating frequency range and band allocation.

Various useful processes could be implemented without modifying the algorithm, a few examples are: idle time and QoS. In many environments, particularly in those associated with e-Health, energetically self-sustainable nodes are desirable. A node equipped with an energy-harvesting device and its energy reserve is low can insert an idle-time process into the packet transmission cycle to allow the device to recharge, by trading-off throughput, as suggested in [8][9]. Another advantage of PSMA is that QoS can be easily implemented, for example, if the information is time sensitive, the algorithm can switch to smaller and more frequent process reservations such that the effective throughput remains the same but the stream is more continuous. Also, different priority level traffic can have different reservation frequency privileges and different reservation time frames. A graphical comparison between TDMA and PSMA is portrayed in Figure 2.

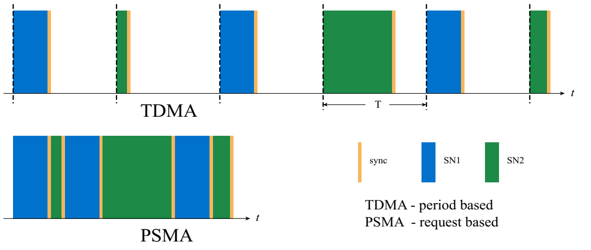

Figure 2. Comparison between time allocation schemes PSMA vs TDMA

II. PROCESS-STACKING MULTIPLEXING ACCESS (PSMA)

PSMA, like TDMA, perform multiplexing access in the time domain. PSMA schedules processes; this means that time is reserved when requested and for the time requested. To organize transmissions a global time pointer is used. In the event that a process or node requests the use of the

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antenna, this process is scheduled at the time stored in the global pointer and the pointer is shifted by the amount of time requested, in practice a buffer time is also inserted. If the current time reaches the global pointer time, then the node switches to listen mode.

A. *Serviced node (SN) encapsulator operation*

Packets flow through the following elements: incoming port, queue, packet encapsulator, main processor, and antenna. The packet encapsulator has a crucial role in the PSMA scheme. It gathers the network layer packets (typically IP) coming from the queue and encapsulates these into a frame. Once the frame is built, its size is translated into a synchronization time using the transmission bit rate. The time, which is used to synchronize this frame, is inserted in a previously stored frame. The previous frame is sent to the main processor for transmission, while the recently encapsulated frame is temporarily stored. Since the recently built frame triggers the transmission of the previously stored frame, this process is referred to as a push (i.e. the arriving frame pushes the stored one). This continues until the queue is empty. To better illustrated this process see Figure 3.

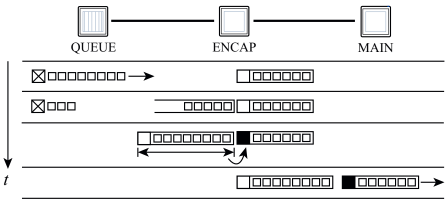

Figure 3. Inter-process Communication in the SN

B. *Communication Dynamics of PSMA*

To stack the frames the following rules are applied, see Figure 4. The task of inserting the first SN is trivial, since there are no active transmissions. If various nodes are sharing the channel and an inactive node turns active, such that is must enter the sharing cycle, it will send a hello frame. The processes are stacked such that there is insufficient time to transmit in between frames; this will cause collisions. When a collisions occurs, the WAP sends a new schedule time to the expected SN with the maximum allocation time (assuming the sync field could not be recovered). Since this is the last event a beacon signal is scheduled after this allowing enough time for a hello frame to be retransmitted.

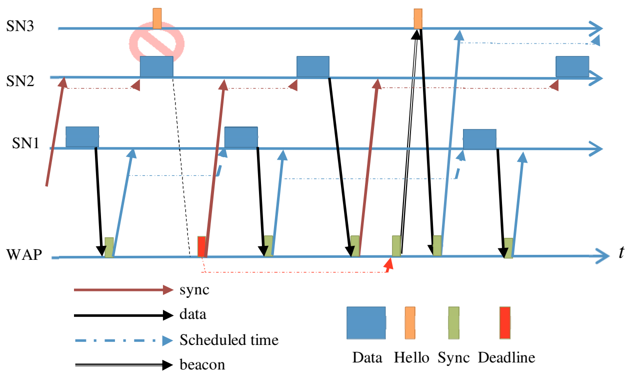

Figure 4. Frame Exchange between multiple SNs and the WAP.

Because there is a scheduled SN the unlinked SN has to wait until the beacon signal to establish a link. Once the WAP has serviced and rescheduled the linked SNs, it sends the beacon signal. The unlinked SN detects that this is a broadcast message (not a hello frame response) and retransmits the hello frame and holds on to the data until the next cycle. The WAP links the SN and from there on frame exchange returns to its routine, but with an additional SN.

C. *Energy Self-sustainability Support under PSMA*

Energy efficiency is an essential property of any wireless system. Self-sustainability is an attractive quality that frees the nodes from a fixed power supply. To support self-sustainability a node must poses an energy harvesting device. Using PSMA an idle process can be inserted in a cyclic Self-sustainability condition:

$$E_{harvested} \geq E_{consumed} \tag{1}$$

$$E_{consumed} = \sum_{\Theta \in \, state} E^{\{\Theta\}} = E^{\{tx\}} + E^{\{rx\}} + E^{\{idle\}} + E^{\{sleep\}} \tag{2}$$

$$E = P \cdot T \tag{3}$$

$$E^{\{\Theta\}} = \sum_{c} \sum_{s} \left(P_{c,s}^{\{\Theta\}} \cdot T_{c,s}^{\{\Theta\}} \right); c \in channel, s \in slot \tag{4}$$

Since only single channel is considered:

$$E^{\{\Theta\}} = \sum_{s} \left(P_{s}^{\{\Theta\}} \cdot T_{s}^{\{\Theta\}} \right) \tag{5}$$

$$P^{\{\Theta\}} = \sum_{s} \left(P_{s}^{\{\Theta\}} \right) \quad and \quad T^{\{\Theta\}} = \sum_{s} \left(T_{s}^{\{\Theta\}} \right) \tag{6}$$

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

$$E_{net} = P^{\{h\}} \cdot T^{\{h\}} - E^{\{tx\}} - E^{\{rx\}} - E^{\{idle\}} - E^{\{sleep\}} \tag{7}$$

Since harvesting is done at all times then:

$$\begin{aligned} E_{net} = {} & \left(P^{\{h\}} - P^{\{tx\}} \right) \cdot T^{\{tx\}} + \left(P^{\{h\}} - P^{\{rx\}} \right) \cdot T^{\{rx\}} \\ & + \left(P^{\{h\}} - P^{\{idle\}} \right) \cdot T^{\{idle\}} + \left(P^{\{h\}} - P^{\{sleep\}} \right) \cdot T^{\{sleep\}} \end{aligned} \tag{8}$$

Using (1) and (8) and solving for $T^{\{sleep\}}$:

$$\begin{aligned} T^{\{sleep\}} = {} & \frac{\left(P^{\{tx\}} - P^{\{h\}} \right) \cdot T^{\{tx\}} + \left(P^{\{rx\}} - P^{\{h\}} \right) \cdot T^{\{rx\}}}{\left(P^{\{h\}} - P^{\{sleep\}} \right)} \\ & + \frac{\left(P^{\{idle\}} - P^{\{h\}} \right) \cdot T^{\{idle\}}}{\left(P^{\{h\}} - P^{\{sleep\}} \right)} \end{aligned} \tag{9}$$

Therefore a self-sustainable system is achieved by selecting the appropriate value for $T^{\{sleep\}}$.

III. RESULTS

The simulation scenario consists of one WAP servicing 4 SNs. All nodes have a bit rate of 1 Gbps. The scenario is built in OPNET modeler 16.0.

A. *Scenario 1 - Systematic Synchronization Capability*

The starting times are pseudorandom with a uniform distribution within a 0.2 second interval. The starting times of the four SN nodes are: 0.0108, 0.0705, 0.1129, and 0.1493 seconds, but do not transmit data until 0.0108, 0.0901, 0.1488, and 0.2075 seconds, respectively, as observed in Figure 5. This simulation run has several interesting aspects: SN1 enters at the same time it requests to enter since it is the only active node at that instant. At 0.0705 s SN2 requests the use of the channel and causes a collision. When the deadline for SN1 expires it is rescheduled; since it is the only node this occurs immediately. It is assumed that upon collisions the sync field is unrecoverable, so the maximum allocation time is granted (in this case 8.3 ms) for the next transmission. It can be seen that SN1 does not require the full allocated time and a gap is produced. Near the end of the gap a beacon frame is sent and the SN2 is linked, but does not transmit data until the following iteration (shown in red). SN3 requests to use the channel at time 0.1129 s. It can be seen that it collides with SN2. SN2 is rescheduled and following this the beacon frame (near 0.13 s), at which time SN3 is linked. In the next cycle SN3 transmits data. SN4 achieves a link in the same way SN2 and SN3 accomplish it. This shows the implementation is successful at establishing links, handling collisions and organizing transmissions in a systematic manner.

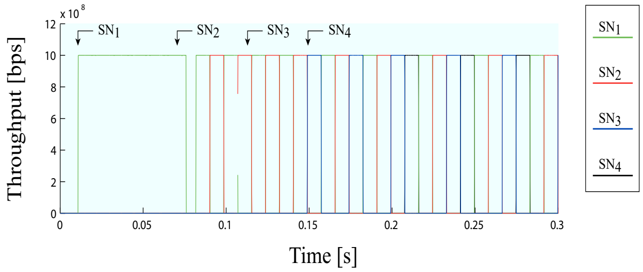

Figure 5. Interlacing of serviced nodes data multiplexed with PSMA.

B. *Scenario 2 – Diverse SN Load Transmission*

To demonstrate the performance capabilities of PSMA it is compared with the legacy TDMA. In this scenario SN1 transmits 34950 packets, SN2 69900 packets (SN1x2), SN3 139800 packets (SN1x4), and SN4 279600 packets (SN1x8), and the results are shown in Figure 6. The implementation of TDMA used reserves a time slot for each node and does not have knowledge about the amount of packets that need to be serviced. In this scenario TDMA takes approximately 13.4 seconds to complete all transmissions. Because PSMA stacks all pending events, it achieves to transmit the same load in approximately 6.3 seconds, approximately half the time consumed by TDMA.

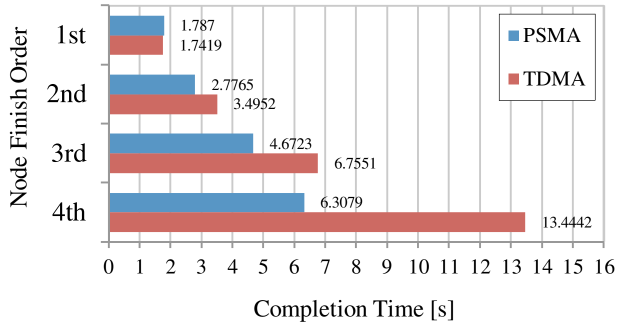

Figure 6. Diverse load transmission using TDMA and PSMA

C. *Scenario 3 – Relative Percentage Loads*

In this scenario SN4 transmits a fixed number of packets (699000), while all remaining nodes transmit a percentage of this load. Results are shown in Figure 7.

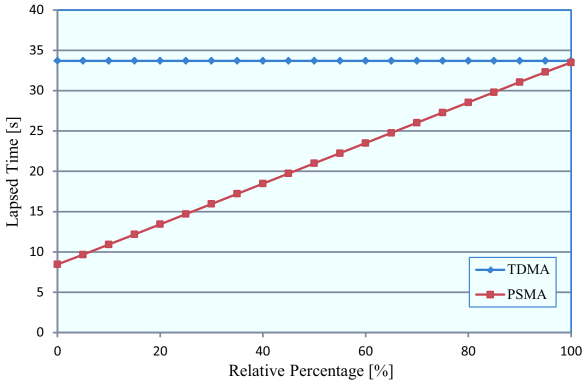

Figure 7. Transmission duration time for varied load percentages.

Since TDMA reserves the slot times independently of there usage, SN4 is unable to take advantage of the unused portions. Regardless of the amount of traffic delivered by the other nodes (as long as it is less than SN4), SN4 will occupy the same amount of time, in this case 33.48 seconds. For the case of PSMA, the processes are stacked, so there is no unused time. If no packets are transmitting, SN4 will use the full channel bandwidth. Compared with TDMA it will improve the effective throughput by a factor proportional to the number of nodes present in the network.

D. *Self-sustainability Scenario*

In this scenario all four nodes have queued packets at all times, therefore never close the transmission link. An energy balancing process is inserted after every node in the cycle has transmitted.

TABLE I. ENERGY AND POWER PARAMETERS

Description	Symbols	Value
system supply voltage	V_{cc}	3 V
time in sleep mode	T_{sleep}	0-10000 ms
max unit length of time slot	T_u	8.3 ms
energy from harvesting	P_{eh}	100 uJ/s
energy capacity of battery	E_{bat}	5 Joule

Operation Mode	Current	Power
RM Sleep	0.02 mA	0.06 mW
SM Sleep	0.3mA	0.9mW
Synchronization	2 mA	6 mW
Idle listen	1 mA	3 mW
Receiving	3.1mA	9.3 mW
Transmitting	3.3 mA	9.9 mW

The overall throughput will decrease as the sleep time increases. The sleep time necessary to achieve self-sustainability will increase as the energy harvesting rate P_{eh} approaches the sleep-time mode power consumption P_{slp}, where this time will not exist if $P_{eh} < P_{slp}$. A device that can harvest at a rate of 700 μJ/s can obtain self-sustainability with a sleep time of approximately 100 ms, as observed in (left) Figure 8. To obtain the overall effective throughput for a given sleep time is trivial. Before explaining it should be clear that by overall it is meant the combined throughput of the all the nodes, i.e. the channel throughput; and by effective it is meant that calculations include the sleep time (idle time) and it is not referred to the bit rate, which is fixed at 1 Gbps. After the sleep time is included the throughputs obtained are plotted in (right) Figure 8.

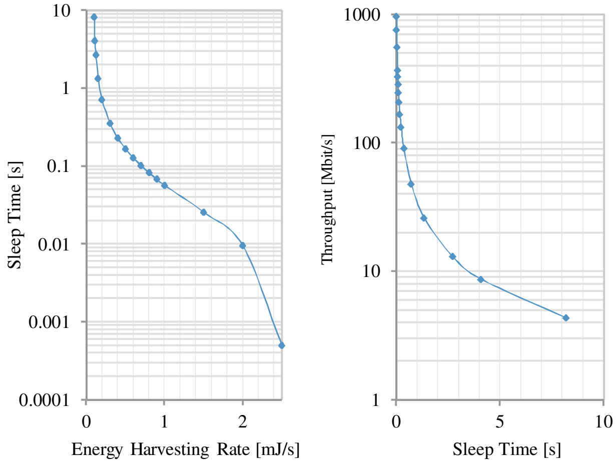

Figure 8. Sleep time requirements for energy harvesting and throughput

If the information from the previous plots is combined, it yields a useful plot, which shows directly the relationship between the energy harvesting rate and the overall effective throughput. This is interesting since given the energy harvesting rate of a particular technology, the corresponding overall effective throughput to achieve self-sustainability is directly obtained. Most energy harvesting devices can only achieve approximately 100 µJ/s, including thermoelectric harvesters. The advantage of thermoelectric devices is that these can placed in series inside clothes increasing the energy harvesting rate. Even with current technology, such as Micropelt's thermoelectric powered node [10], this is feasible, particularly if its size can be reduced. This makes this technology attractive for BAN technologies. Three of these devices in series would suffice to reach 100 Mbps transmissions, as seen in Figure 9.

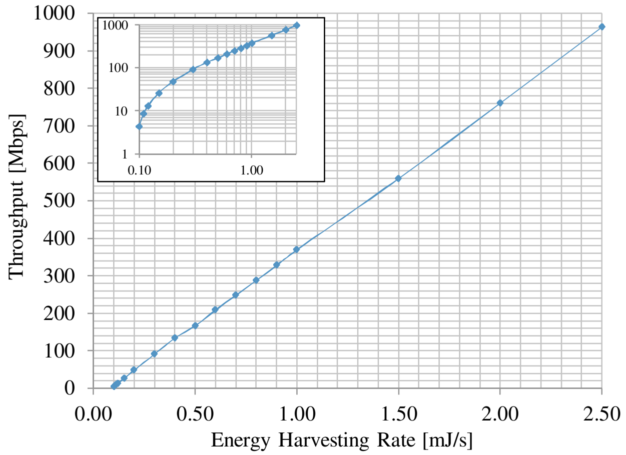

Figure 9. Overall Effective Throughput versus Energy Harvesting Rate

The results from all scenarios demonstrate that PSMA is an energy-effective, versatile, and a time-efficient solution over the legacy TDMA. Also, because energy-harvesting of thermoelectric devices is maturing, e-Health applications using BANs can benefit from energy self-sustainability.

IV. CONCLUSIONS

PSMA is an efficient time-domain multiplexing access technique. It has many advantages over legacy TDMA: PSMA has a very efficient use of time as it not only stacks processes that actively require the use of the channel but it allocates only the necessary amount of time for this process to complete. PSMA is versatile in the sense that in can easily schedule processes not related to data exchange without affecting significantly the transmission of the linked SNs. PSMA supports QoS, as different priority levels can have different benefits. Along with energy harvesting devices PSMA can achieve self-sustainability, which is an attractive quality for e-Health applications using BAN technology. It is shown conceptually that using existing thermoelectric harvesters a BAN can reach 100 Mbps while maintaining a constant power level, becoming completely independent of a fixed power source and therefore a fully mobile technology.

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