A Novel Concept of UWB Pulse Switching in Sensor Networks

Qiong Huo and Subir Biswas
Michigan State University, USA
qionghmsu@gmail.com, sbiswas@egr.msu.edu

Abstract **-This paper presents the initial results of applying a novel concept of energy-efficient pulse switching protocol for ultra-light-weight wireless network applications. The key idea is to abstract a single pulse, as opposed to multi-bit packets, as the information exchange mechanism. Pulse switching is shown to be sufficient for event sensing applications with binary sensing. Event sensing with conventional packet transport can be prohibitively energy-inefficient due to the communication, processing, and buffering overheads of the large number of bits within a packet's data, header, and preambles. The paper presents the key architectural ideas of a joint MAC-Routing protocol for pulse switching with a novel hop-angular event localization.**

Keywords-Impulse Radio; Pulse Switching; UWB; Sensor Network; Event Monitoring; Pulse Routing

I. INTRODUCTION

The key idea in this paper is to introduce a new abstraction of *pulse switching* for replacing the traditional packet switching for event monitoring. An example application is *Structural Health Monitoring* (SHM) [1] in which while monitoring a bridge for structural failures, it may be sufficient for a sensor to generate an event to indicate a structural crack in its vicinity. Sending an event, indicating the presence of the crack, to a sink would require single bit information transport. For this scenario, packets can be energy inefficient due to the communication, processing, and buffering overheads of a large number of bits within the payload, header, and the synchronization preambles [2] in each packet.

In the proposed pulse switching paradigm, such an event can be coded as a single pulse, which is then transported multi-hop while preserving the event's localization information. The resulting operational lightness, leveraged via zero collision, zero buffering, no addressing, no packet processing, and ultra-low communication and energy budgets makes the protocol applicable for severely resource-constrained sensor devices such as Radio Frequency Identifiers (RFIDs) operating with tight energy budgets, often from harvested energy [3].

The primary challenges are: 1) how to transport localization information using a single pulse, and 2) how to route a pulse without being able to explicitly code any information within the pulse. A key architectural novelty in this work is to integrate a pulses' (i.e. event's) location of origin within the MAC-routing protocol syntaxes. More specifically, by observing the time of arrival of a pulse with respect to the MAC-routing frame, a sink can resolve the corresponding event location with a pre-set resolution. Multi-hop pulse routing is addressed by introducing the concept of a novel *synchronized phase waves* across different hop-distances from the sink.

The rest of the paper is organized as follows. Section *II* presents the related work. Section *III* describes the network, application, and localization model. Section *IV* presents the MAC-Routing pulse switching architecture, and Section *V* presents simulated performance results of the proposed architecture. Finally, Section *VI* summarizes the paper.

II. RELATED WORK

Jain et al. [4] reduce preamble and header overheads by aggregating payloads from multiple *short* packets into a single *large* packet that is routed to a sink node. While reducing the energy cost, aggregation still requires the inherent packet overheads. The objective of our work is to fully eliminate packets via replacing them by pulse switching.

Fragouli et al. [5] develop models for energy and delay bounds for bit (i.e., packet based) and pulse communications in single hop networks. The main results are to demonstrate that the worst case energy performance of pulse communication can be substantially better than that of packet based communication, although with a possibly worse delay performance. A notable limitation of this work is that the paper does not provide mechanisms for scaling these results for multi-hop networks. Also, no Medium Access Control (MAC) and routing protocol details are provided for pulse switching. The objective of this paper is to design a MAC-routing framework that can be used for practical implementations of multi-hop pulse switching.

III. NETWORK AND APPLICATION MODEL

Network Model: As shown in Fig. 1, a network contains arbitrarily distributed sensors that send pulses to a sink. Depending on the node locations and the transmission range (assumed to be non-uniform), each node resides at a certain *hop-distance* from the sink. In Fig. 1, the hop-distance for each node is marked under the node. The sink is assumed to be capable of making high-power transmissions with full network coverage for frame-synchronizing the sensors.

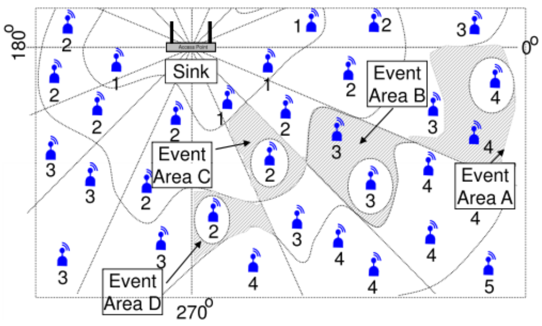

Figure 1. Network model with hop-angular localization

Application Model: Pulse switching can be used for event sensing applications. An event results in multiple pulses, which are transported multi-hop to a sink. A pulse is able to represent: a) the very occurrence of the event, and b) its location of origin. With this information, several high level conclusions can be derived at the sink by correlating multiple event pulses.

Hop-angular Event Localization: A concept of *hop-angular event area* is introduced for event localization. The network is logically divided into a fixed number of angular sectors. In Fig. 1, for example, there are 16 22.5°-wide sectors. With a predefined sector-width (α^o), the location of a sensor can be represented by the tuple {*sector-id, hop-distance*}. For example, the location of the encircled sensor in Event Area *B* in Fig. 1 can be represented as {*15, 3*}, meaning the node is located in the 15th sector, with a hop-distance 3 from the sink.

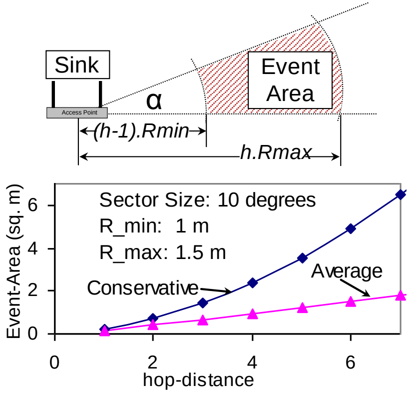

Figure 2. Hop-distance event localization

The concept of event area does not assume any specific shape (i.e. circular or otherwise) of a node's transmission coverage area. It could be of any arbitrary shape as shown in Fig. 1. While the angle for a node is pre-programmed at the deployment time, its hop-distance can be dynamically discovered using the process outlined in Section IV.C. The {*sector-id, hop-distance*} tuple indicates an *event-area*, whose size determines the event localization resolution. This tuple for an event's origin is carried to the sink by the corresponding pulse.

Consider the example event-area identified by the tuple {α, *h*} in the top portion of Fig. 2. With a sector-width of *α*, and R_{min}, R_{max} representing the known minimum and maximum wireless transmission range, the most conservative (coarse) localization resolution can be expressed as the largest possible event area: $A_{conservative} = \{h^2 R_{max}{}^2 - (h-1)^2 R_{min}{}^2\}\alpha\pi/360$. The average resolution is $A_{avearge} = \{h^2 R^2 - (h-1)^2 R^2\}\alpha\pi/360$, where $R = (R_{min} + R_{max})/2$. For example, with transmission range spanning between 1m to 1.5m, in a network with sector-width (i.e. *α*) of 10°, the size of an event-area that is 5 hop-distances away is approximately 3.5 square meters. For the Structural Health Monitoring application on a bridge, this means that a structural crack can be localized within approximately 3.5 square meter area. For a given *α* and transmission range, since this resolution reduces with higher hop-distances, the maximum network size will be determined based on the desired resolution.

IV. PULSE SWITCHING ARCHITECTURE

A. *Joint MAC-Routing Frame Structure*

Nodes are frame-by-frame time synchronized by the sink, and they maintain joint MAC-Routing frames (see Fig. 3) in which each slot is used for sending a single pulse. The slot includes a guard-time to accommodate the cumulative clock-drift during a frame, which can be very small for RF technology such as Ultra Wide Band (UWB) Impulse Radio, as the frame size itself can be ultra-short (μs) for UWB. As shown in Fig. 3, the frame contains an uplink part and a downlink part. The uplink part contains a control sub-frame and an event sub-frame. The downlink part of the frame contains a synchronization slot in which the sink transmits a *full power* pulse to make all nodes frame-synchronized. The two following downlink slots and the reconfiguration part of the uplink control sub-frame are used for hop-distance discovery. The reconfiguration area in control sub-frame has (*H+1*) slots, where *H* is the maximum hop-distance. The forwarding flag area is designed for routing pulses towards the sink. The *H*-slot wide routing area of the control sub-frame is used for energy management. These functions will be explained in detail in the next few sections.

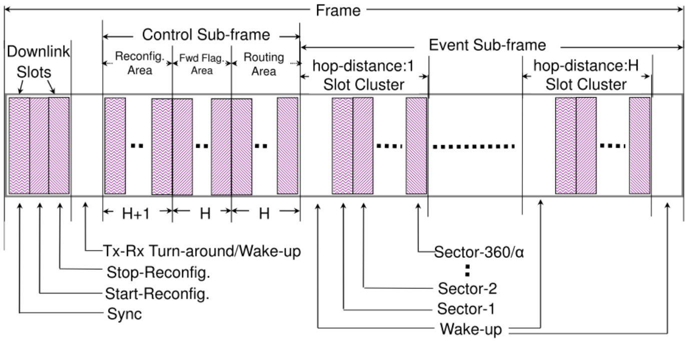

Figure 3. MAC-Routing frame for multi-hop pulse switching

The event sub-frame contains *H* slot clusters, each cluster containing *360/α* slots, where *α* corresponds to the sector-width. Each slot within a cluster corresponds to a specific {*sector-id, hop-distance*} tuple. Meaning, for each event-area, represented by {*sector-id, hop-distance*}, there is a dedicated slot in the event sub-frame. An event originating node transmits a pulse during the dedicated event sub-frame slot that corresponds to the {*sector-id, hop-distance*} of the node's event area. While routing the pulse towards the sink, at all intermediate nodes it is transmitted at the same event sub-frame slot that corresponds to the {*sector-id, hop-distance*} of its event-area of origin. In other words, while being forwarded, the transmission slot for the pulse at all intermediate nodes does not change with respect to the frame. This is how information about the location of origin of an event is preserved during routing. Upon reception, the sink can infer the event-area of origin from the {*sector-id, hop-distance*} value corresponding to the slot at which the pulse is received. The role of the control sub-frame in Fig. 3 will be described in Sections IV.C, IV.D and V.

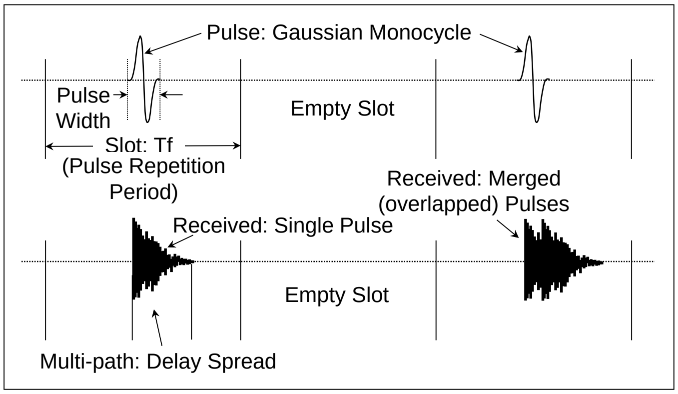

Figure 4. Pulse switching with un-modulated UWB pulses

B. *Pulse Realization using UWB Impulse Radio*

The ability to transmit and receive a single pulse without per-pulse synchronization overhead is a key requirement for pulse switching. Ultra Wide Band (UWB) [6][7] Impulse Radio (IR) technology can be practically [8] used because of its support of single pulse transmission and reception. The top graph in Fig. 4 depicts a UWB implementation of the slot structure used in this protocol. A typical UWB pulse width is *1 ns*, and the pulse repetition period T_b is *1000 ns* [6], which determines the slot size in this case.

C. Pulse Forwarding

A hop-distance discovery process needs to be periodically executed by the network for each node to discover its own hop-distance from the sink node. When a pulse is transmitted by a node at hop-distance *h*, only its neighboring nodes at hop-area (*h-1*) forward it towards the sink. Meaning, the nodes at hop-area *h* and *h+1* should ignore the pulse. This logic ensures that a pulse is eventually delivered to the sink. While transmitting a pulse in the event sub-frame (see Section IV.A), its transmitter also sends a pulse in the corresponding slot of the *forwarding flag* area of the control sub-frame. That is, while forwarding a pulse by a hop area *h* node, it sends a pulse in the h^{th} time slot of the *forwarding flag* area. By looking at the received pulse in the *forwarding area*, all the receivers of the pulse can decide if it should be discarded or forwarded towards the sink. This can ensure that a pulse from hop-area *h* should be forwarded only by nodes in hop-area *h-1*.

D. Sector-constrained Routing

The extent of *sector-constraints* during pulse forwarding can be parameterized using δ, which represents the ratio of the angular resolution α and an angle γ. The angle γ is the sector-width beyond which a pulse may not be flooded while forwarding. For a given α, the minimum and the maximum values of γ are α and 180^o respectively.

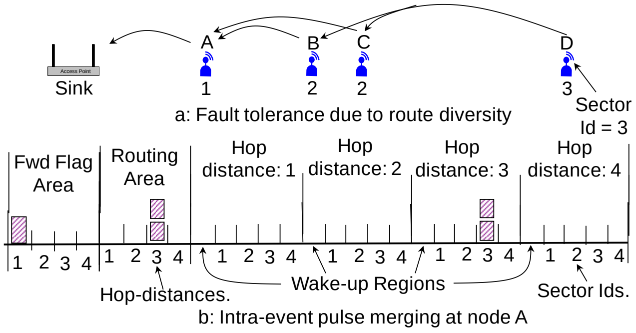

Figure 5. Route diversity and pulse merging/aggregation

The corresponding δ values are 1 and $180^o/\alpha$. When δ is 1, routing is maximally constrained, indicating the minimum communication energy consumption, and the maximum susceptibility to errors due to the minimum pulse redundancy, as shown in Fig. 6.

E. Aggregation via Pulse Merging

Collisions between pulses may not necessarily lead to information loss. For example, in Fig. 5, since the pulse originating from D is transmitted by *B* and *C* on the same slot in the event sub-frame, the receiver *A* detects RF signals for a merged pulse in that slot. As long as the RF hardware can detect the presence of this overlapped pulse, the routing continues. In fact, this pulse merging and route diversity provides inherent in-network aggregation for events from the same event-area.

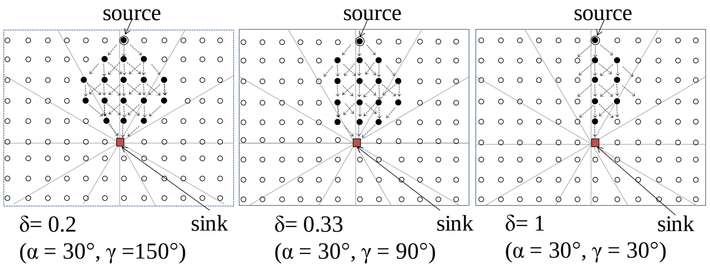

Figure 6. Routing envelope and pulse fan-out during forwarding

V. PERFORMANCE EVALUATION

We developed an event-driven C++ simulator which implements MAC framing and pulse routing using the UWB Impulse Radio model as presented in Section IV.

A. Pulse Transmission Count

For the proposed Pulse Switching Protocol (PSP), Fig. 7:a reports the number of forwarding transmissions across different hop areas when an event is created in hop area 5 in the 441 node network. Numbers are reported for two different sector constraints (δ=0.2 and 1). For both δ observe how the number of pulse transmissions maximizes at an intermediate hop-distance, confirming the lateral fan-out and convergence seen as the routing envelopes in Fig. 6.

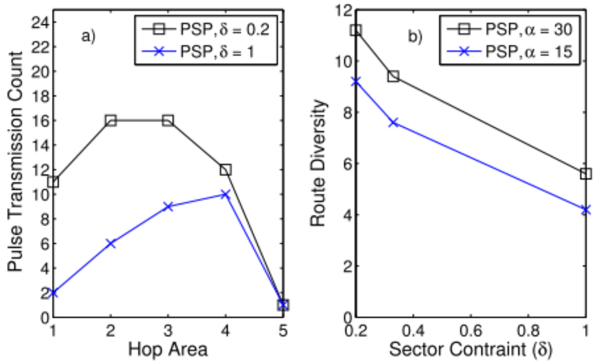

Figure 7. Transmission count and route diversity

B. Route Diversity

The route diversity factor β ($\beta \geq 1$) represents the number of forwarding transmissions for a pulse from hop-distance *h*, normalized by *h*, which is the minimum number of required transmissions. Fig. 7b demonstrates β with increasing sector-constraint δ for two different angular resolutions of α = 15° and 30°. A larger α means more nodes are involved in forwarding (see Fig. 6), leading to higher route diversity.

C. Error Analysis

Impacts of Pulse Loss Error: Pulse losses can manifest in the form of un-reported events. We define *Pulse Loss Rate (PLR)* as the probability that a pulse is lost in a given time-slot due to multi-path, channel noise, or interferences. *Event Loss Rate (ELR)* is the probability that a pulse is not reported to the sink. Fig. 8:a depicts simulation results of PLR versus ELR for a single event generated in hop area 5 of the 441-node network. Observe that for practical range of PLR [10], the ELR for PSP remains vanishingly small and it is generally insensitive to the value of PLR. This is mainly because of the redundancy in pulse transmissions (i.e. route diversity) for PSP as demonstrated in Fig. 7.

Impacts of False Positive Errors: If pulses are erroneously detected [9] by a node in state *LO* or *TL* such that a false positive pulse in the control sub-frame corresponds to another false positive pulse in the event sub-frame with corresponding forwarding flag (see Fig. 3), then an event is falsely detected at that node. Once such a false positive event is generated, it is forwarded all the way to the sink, leading to a false positive event reporting. Let *FPPR* (False Positive Pulse Rate) be the probability that a false positive pulse is generated due to faulty UWB detection in a given time-slot. We intend to determine the quantity *FPEGR* (False Positive Event Generation Rate) which corresponds to the probability of at least one false positive event generation per frame per node at a given hop-area.

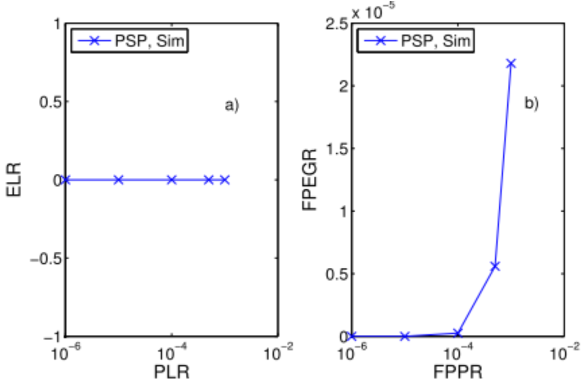

Figure 8. Impacts of pulse loss and false positive

The impacts of *FPPR* on *FPEGR* in hop area 3 in PSP are shown in Fig. 8:b. Hop area 3 is chosen because it represents the middle of the experimental network. Observe that in PSP, *FPEGR* is extremely small with practical range of *FPPR* [10] which is lower than 10^{-4}. This indicates that the proposed PSP is fairly immune to false positive errors.

D. Energy Consumption

A distributed TDMA with sink-rooted minimum spanning tree for packet routing has been used as the representative protocol to compare its energy consumption with that of the proposed pulse switching. TDMA is chosen because of its high energy efficiency compared to random access mechanisms. An event detected by a sensor is reported to sink using min-hop routing along the minimum spanning tree. A packet contains the minimum amount of information to represent a {*sector-id, hop-distance*} event-area and also a per-packet preamble [2].

Based on the UWB specification [8], the transmission and reception consumptions are set to *4 nJ* and *8 nJ* per pulse. Since a pulse transmission using the baseband UWB has the same energy expenditure for Pulse Position Modulated bits in a packet, the same *4 nJ* and *8 nJ* values are used for both pulse and bit (in packets) transmission and reception.

Fig. 9 reports the communication power consumption for both pulse and packet transport with varying event rates. Observe that the consumption is linearly dependent on the event rate λ for both pulse and packet scenarios. The slope of the TDMA graph in Fig. 9 is noticeably higher than that for PSP for both angular resolutions of $\alpha = 15^{\circ}$ and 30°, and it is mainly due to the overhead of per-packet preamble and payload overheads. Overall, Fig. 9 validates the primary premise of pulse switching that it can transport multi-point-to-point binary events at a lower energy budget compared to traditional packet switching.

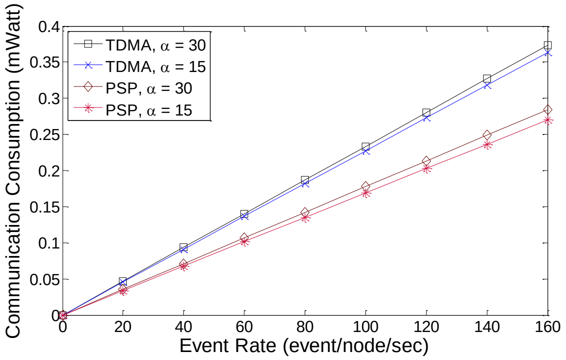

Figure 9. Communication power consumption per node

VI. CONCLUSIONS AND FUTURE WORK

A novel pulse switching protocol for ultra-light-weight networking applications has been developed in this paper. A joint MAC-routing architecture for pulse switching with a hop-angular event localization strategy was presented. Through simulation results, it is shown that the proposed pulse switching architecture can be an effective means for energy efficiently transporting information that is binary in nature.

Future work on this topic includes: 1) an implementation of the proposed pulse routing architecture on a UWB embedded hardware, 2) extending the architecture for cellular event localization, and 3) experimenting with pulse switching for non-radio media such as ultrasound on metal substrates.

VII. ACKNOWLEDGEMENT

This work was supported by an NSF grant NeTS 0915851.

VIII. REFERENCES

[1] C.R. Farrar, G. Park, D.W. Allen, and M.D. Todd, “Sensor network paradigms for structural health monitoring”, J. of Structural Control and Health Monitoring, vol. 13, no. 1, 2006, pp. 210-225.

[2] Z. Yuanjin, C. Rui, L. Yong, “A new synchronization algorithm for UWB impulse radio communication systems”, Int. Conf. on Communication Systems (ICCS), Singapore, 2004, pp. 25-29.

[3] E. Minazara, D. Vasic, and G. Poulin, “Piezoelectric diaphragm for vibration energy harvesting”, Ultrasonics, vol. 44, no. 1, 2006, pp. 699-703.

[4] A. Jain, M. Gruteser, and D. Grunwald, “Benefits of Packet Aggregation in Ad-Hoc Networks”, Technical Report CU-CS-960-03, Dept. of Computer Science, Boulder, Colorado, August, 2003.

[5] C. Fragouli and A. Orlitsky, “Silence is golden and time is money: power-aware communication for sensor networks”, in Allerton Conference on Comm., Control and Computing, 2005.

[6] S. Haykin and M. Moher, “Modern wireless communications”, Prentice-Hall, Inc., 2004, Upper Saddle River, NJ, USA.

[7] M. Win and R. Scholtz, “Impulse radio: how it works”, IEEE Communication Letters, vol. 2, no. 2, 1998, pp. 36-38.

[8] B. Poucke and B. Gyselinckx, “Ultra-wideband communication for low-power wireless body area networks”, Industrial Embedded Systems Resources Guide, 2005.

[9] Van Trees and Harry L., “Detection, Estimation, and Modulation Theory - Part l.” John Wiley & Sons.

[10] Yu. Andreyev, A. Dmitriev, E. Efremova, A. Khilinsky and L. Kuzmin, “Qualitative Theory of Dynamical Systems, Chaos and Contemporary Wireless Communications”, International Journal of Bifurcation and Chaos, Vol.15, No.11, 2005, pp. 3639-3651.