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A pulse switching paradigm for ultra low power cellular sensor networks☆

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ABSTRACT

This paper presents a novel energy-efficient and fault-tolerant pulse switching protocol for ultra-light-weight wireless cellular network applications. The key idea of pulse switching is to abstract a single pulse, as opposed to multi-bit packets, as the information exchange mechanism. In this paper it is shown to be sufficient for event and target tracking applications with binary sensing in terms of cellular localization. Event monitoring and target tracking 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. Additionally, both of them can be unreliable without protection from errors and faults occurrence. The paper presents a joint MAC and Routing architecture for pulse switching with a novel cellular event localization in the presence of errors and faults. Through analytical modeling and simulation experiments, it is shown that cellular pulse switching can be an effective means for event based networking, which can potentially replace the packet transport when the information is binary in nature.

1. Introduction

1.1. Motivation and objective

The objective of this paper is to develop a novel Ultra Wide Band (UWB) pulse switching framework that uses a cellular network and localization structure to implement packet-less event communication. The key idea is to introduce a new abstraction of *sensor event area cells* and to use it for extending our previous work [1] on *packet-less pulse switching* for monitoring infrequent events and tracking slow-moving targets. An example application is intrusion detection in which while surveying a building it is often sufficient for a sensor to generate an event to indicate an intrusion in its vicinity. Sending an event to a sink ideally requires a single bit information (i.e. binary information) transport for which the traditional mode of packet communication can be highly energy inefficient. Such inefficiency stems from communication, processing, and buffering overheads of a large number of bits within the payload, header, and the synchronization preambles [2] in each packet. Another example application of the proposed mechanism is structural health monitoring for infrequent fault events.

Unlike multi-bit packet communication, the proposed cellular paradigm is based on pulse communications where a node either transmits a pulse or keeps silent to send binary information. A pulse is realized as a short burst of baseband signal. An event is coded as a single pulse which is transported multi-hop to a sink while preserving the event's localization information

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in the form of the pulse's temporal position within a synchronized frame. The resulting operational lightness, leveraged via no addressing, no packet processing, and ultra-low communication and energy burdens make the protocol applicable for severely resource-constrained sensor devices.

1.2. Challenges and contributions

The primary challenges for pulse networking are how to: (1) transport localization information using a single pulse, and (2) route a pulse multi-hop. These problems are architecturally solved by integrating a pulse's (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 a MAC-routing frame, a sink can resolve the corresponding event location. The problem of multi-hop pulse routing is solved by introducing a novel concept of *cellular event area* combined with *synchronized pulse frames*.

The contributions of this paper are: (1) development of a *sensor-cell* based event localization architecture, (2) integration of such localization with a *pulse-switching* protocol paradigm and its associated MAC and routing syntaxes for multi-hop operations, (3) development of mechanisms for added network resilience and energy efficiency, (4) analytical modeling for error handling measures and finally, (5) simulation evaluation of pulse switching for event monitoring in a cellular sensor network.

1.3. Protocol scope and requirements

The applicability of the proposed event networking architecture is scoped as follows. First, it is targeted mainly to small networks with few tens of sensor cells distributed within a restricted geographical area. Although it may not scale well for very large networks, the protocol can enable low-frequency intrusion detection and event monitoring for targeted applications such as structural health monitoring for aircraft wings, bridges, and other small structures [3]. Such target applications are geared towards customized applications where the network size (i.e., number of sensor cells) is known a-priori, e.g., aircraft wings, bridges, and small structures. Second, the energy benefits of the architecture are predicated on the assumption of low event frequency, which is often true for structural fault monitoring and intrusion detection type applications. Third, a central requirement is the ability of the sink to synchronize the entire network via high power pulse transmissions which makes sense in the presence of an energy-unconstrained access point (see Section 5.2). For applications such as bridge and structure monitoring, this is reasonable since an energy-unconstrained sink, which can be plugged into mains power, can enable the distributed and embedded sensors to operate with ultra-thin energy budgets. Finally, the proposed mechanism in this paper is meant for single-sink scenarios. Using multi-band operation and syntax extensions, multiple simultaneous sinks can potentially be supported.

1.4. Paper structure

The rest of this paper is organized as follows. Section 2 discusses related work. Ultra Wide Band physical layer issues that are relevant to pulse switching are presented in Section 3. Network topology and application abstractions are presented in Section 4. Section 5 presents the proposed baseline cellular pulse switching architecture in details. Section 6 develops fault-tolerance mechanisms on top of the baseline protocol. Specific energy saving protocol syntax for the proposed protocol is developed in Section 7. Section 8 constructs analytical models for the impacts of pulse errors and the effectiveness of proposed error handling measures. Section 9 analyzes the delay and energy of pulse switching compared with traditional packet-based solution. The performance evaluations and summary of the proposed pulse switching protocol are respectively provided in Sections 10 and 11.

2. Related work

Very few efforts exist in the literature on packet-less networking using pulse communication. The paper in [4] reduces preamble and header overheads of packet communication by aggregating payloads from multiple *short* packets into a single *large* packet that is routed to a sink. While reducing the energy cost, aggregation still requires the inherent packet overheads. For target tracking applications, [5] proposes a binary sensing model in which each sensor returns only one-bit information regarding a target's presence or absence within its sensing range. Although this binary sensing saves energy to some degree, the approach in [5] too uses a packet abstraction. The objective of our work is to fully replace packets by routable pulses.

The paper in [6] proposes a wireless MAC protocol that utilizes out-of-band contention pulses for packet collision detection. Unlike the solution proposed in this paper, pulses in [6] are of varying length, rendering technologies such as UWB-IR unusable. Additionally, although pulses are used for handling collisions, traditional packets are still used for sending information. Therefore, the PDU related overheads of packet switching are present in the solution in [6].

Idling energy reduction in synchronous packet-based MAC protocols such as T-MAC [7] is accomplished via interface sleeping in appropriately scheduled packet slots. Idling in asynchronous protocols such as B-MAC [8] is reduced by relying on low power listening, also called preamble sampling, to link together a sender to a receiver that is duty cycling. Hybrid protocols also exist that combines a synchronized protocol like T-MAC with asynchronous low power listening [9]. Distributed TDMA protocols [10] avoid idling consumption by turning interface off in all packet slots except when needed

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