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Component-based Wireless Sensor Networks

A Dynamic Paradigm for Synergetic and Resilient Architectures

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***Abstract*—Wireless Sensor Networks (WSNs) are approaching an operational stalemate. While sheer emphasis on energy efficiency and resilience aid network longevity, WSNs face many hindering design principals. Prominently, an application-oriented view that isolates WSNs from ubiquitous networks, and nodes with static hardware and functional goals. We present a novel paradigm in the design of WSNs. Our goal is to achieve a resilient architecture that decouples operational mandates from the nodes. We present wirelessly interfaced components, which introduce functionality physically decoupled from the sensing nodes; boosting resilience, dynamicity and resource utilization. This approach dissects the study of nodal capacity to its "connected" components. It also enables re-introducing only the components required to suffice for network operation. More importantly, critical resources in the network will be shared within their neighborhoods. Thus network lifetime will relate to functional *cliques* of dynamic nodes. We present our paradigms with insights into application and design novelty.**

***Index Terms*— Resilient Protocols, Sensor Networks. Novel Paradigm, Dynamic Topology, Dynamic Components, Parallel-assignments, Heterogeneous architecture**

I. INTRODUCTION

Early designs of Wireless Sensor Networks (WSNs) started with a simple notion of operation. A group of wirelessly connected nodes should form a network once deployed, and commence sensing and reporting back to a central location (a sink) to aggregate their findings. Each of the nodes would be equipped with four main components, a processor, sensing unit, transceiver and power unit [1].

This paradigm dictated a strong adherence in operation between the four main components, and other auxiliary units were introduced incrementally to add to functionality and lifetime. These include power harvesting, localization (eg. GPS), mobility and other units. As such, much of the literature on WSNs was built upon the notion of a network of nodes, with pre-defined capabilities, that are deployed to meet a certain application requirement.

This mainstream approach to WSNs suffers from two main bottlenecks. At one end, the dominant application-specific drive hinders WSN synergy with ubiquitous networks. At the other, the notion of a sensing node (SN) as a single entity with static operational goals and functional parameters. This is a by-product of aiming for one-time installations of sensing architectures. Two simple notions hence followed: nodes, once deployed, are static in terms of functionality, and the lifetime of all components on a node are mostly capped by the failure of the first one; being the transceiver, sensor or even the memory unit [2].

As such, we hereby present the Dynamic WSN (DWSN) paradigm. It severs operational capacity from the design phase, and introduces the dynamicity of self-adapting sensor nodes capable of coping with targeted components. These components hold communication interfaces and specific functionalities, which are mapped to WSN requirements. Their locations are adaptive to application requirements, and they are introduced at network deployment and/or later on as a measure of maintenance as the need arises. Thus, the "dynamic" component of DWSN spans both the functional variation through network lifetime, and the (re)association of components with nodes post-deployment. For example, a high-end sensor could be probed by multiple nodes in parallel, instead of mandating a separate installation on specific nodes.

Previous efforts in literature have presented the notion of platforms with multiple components [3], and others focused mainly on multiple transceivers for boosting communication and evaluated their performance [4]. Other studies investigated having multi-level duty cycles, to allow a node to operate in different states based on available resources [5] [6]. However, they mandate fixed application requirements.

DWSN presents two main contributions, (1) assigning network functionality to individual components that are introduced to active sensor nodes to augment their capabilities as needed per function, location and time, and (2) re-engineering WSN operation to accommodate for dynamic architectures that evolve over time to boost resilience and lifetime, based on individual components not static nodes inherently aggregated on single chips. Fig. 1 shows an overview of the DWSN paradigm

DWSN contrasts mainstream WSN research, hence significant emphasis is presented in Section II to identify these mainstreams and elaborate on their evolution. Section III follows with an explanation of the components of the architecture, with an overarching theme of synergy. This is followed by a description of how these components work and communicate, and an analysis of resilience metricized by functionality sustenance in Section IV. This work is concluded with future work and insights into synergetic scenarios in Section V.

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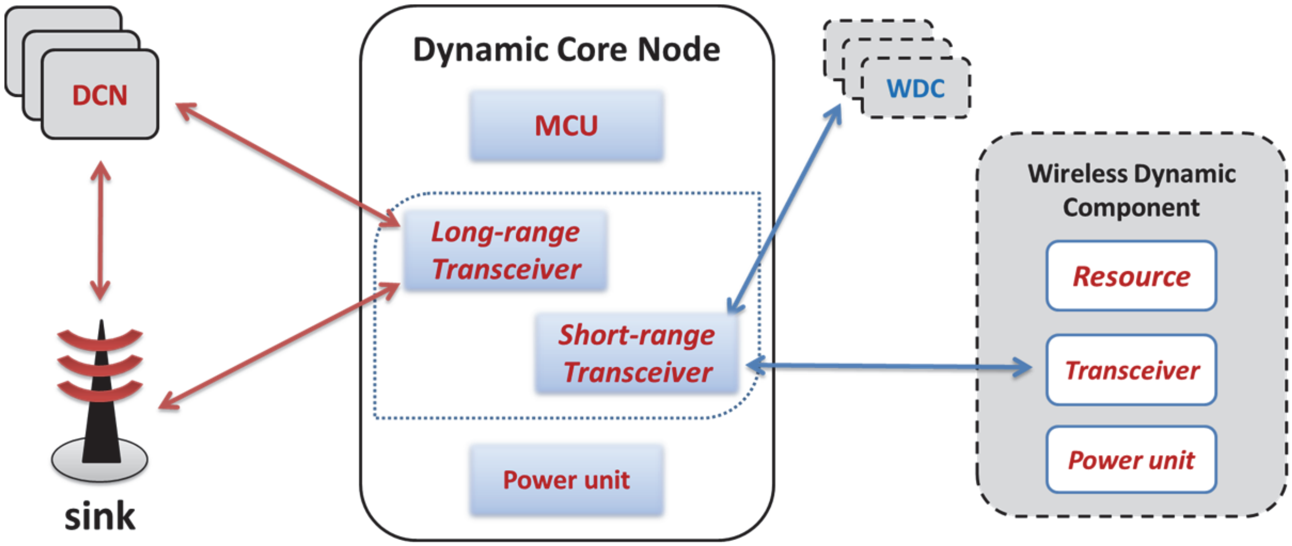

Fig. 1. Dynamic WSN paradigm (DWSN) – Overview of components and their interfaces

II. BACKGROUND

Significant WSN design bottlenecks were inherited from MANETs (Mobile Ad hoc Networks) architectures and protocols. Understanding the evolution of solutions for these bottlenecks offers great insights into today's status quo. Here we approach four directions that have inspired evolution in WSN architectures; yet with their varying constraints.

A. Architectures with redundant components

As requirements for more sophisticated sensor nodes increased, researchers investigated adding more components – possibly redundant ones – to boost performance [5][6]. The extent and deviations varied significantly according to the available platform, compatibility of components, and design requirements. A core motivation was induced resilience.

B. Public Sensing

A newer paradigm of sensing has emerged in a domain called public sensing. It builds upon research in mobile computing and WSNs. The main idea is depending on users with smart-phones, or specially supplied devices, to carry out sensing tasks and reporting it back to a database. Prominent solutions following this paradigm, such as Cosm (previously known as Pachube), have been launched [7].

C. Participatory Sensing Networks

The notion of enticing the crowds to carry out sensing tasks has been approached in many ways; most dominantly now in the domain of participatory sensing networks. Incentive schemes that promote either "reputation" or rewards based on monetary or credit systems, have been seen in many proposals.

Although there is merit in the claim of crowd-intelligence there are many challenges that hinder the wide scale adoption of Participatory Sensor Networks (PSNs). Xie *et al* investigated bargain-based mechanisms to remedy the intrinsic tendency of nodes not to take part in PSNs [8].

D. Nodes with multi-operational levels

As the cost of individual MEMS components (e.g. transceivers, sensors) dropped, a new feasible possibility came to be. Introducing multiple components on the same node, i.e. redundant ones, and experimenting with switching individual components on an off, in studied combinations, to conserve power. Not only would it serve power conservation for network longevity [3], but it also enables introducing higher-end nodes that have multiple capabilities, switched on upon need. DMULD presented in [6] a deterministic operational mandate for a decentralized network of duty cycled nodes.

III. COMPONENT BASED DWSN ARCHITECTURE

DWSN has three core goals. First, to boost dynamicity and generic design as a paradigm shift in WSNs. Second, potentiate a broader platform for application independent components that scale over time. Third, establish a utility-based quantifier to the choice of resources matched to each functional request. That is, establishing a paradigm that would allow different resources to compete for carrying a given task.

A. Network Model

The DWSN will be comprised of three components. First, Dynamic Core Nodes (DCN) which will form the topology of the communicating network. Each DCN will attach itself to one or more Wireless Dynamic Component (WDC). Thus, forming a star-like network association with neighboring WDCs. Finally, DCNs communicate with each other, relaying their data back to a sink. However, the decisions of associations between DCNs and WDCs are made within their vicinities, in a decentralized and homogeneous manner.

B. Dynamic Core Nodes (DCN)

The DCN will form an anchor for multiple operations. It will carry out regular sensing and communication tasks, as per the mandate of the governing application(s). In addition, it will interface to WDCs for one of two reasons. Adopting a functionality that it requires but does not have, or saving its battery/resources and "outsourcing" the required functionality from a neighboring WDC.

In addition, the DCN will have two transceiver units. The first will enable long-range communication, between DCNs and each other, and DCN to sink. Two viable candidates are WiFi or DASH7, as both could sustain long range communication with varying power demands [9]. For example, a typical DASH7-compliant transceiver would achieve a range of 1000m, since it operates on a lower frequency band; 433MHz. The second unit will be a short range transceiver, which would establish a parent-child relationship with neighboring WDCs. This would typically be a ZigBee protocol stack, as it operates in low-power mode, and enables communication under the parent-child paradigm.

C. *Wireless Dynamic Components (WDC)*

The core task of a WDC is to provide functionality to its neighboring DCNs. It could associate with one or more DCNs, depending on its functional resources, remaining energy and current attachments. That is, how many DCNs is it already serving. WDCs are equipped with short-range low-power transceivers, enabling only direct communication with DCNs. As such, a typical choice would be a ZigBee protocol stack, whereby the WDC would function as a ZigBee End Device (ZED) if the DCN is a ZigBee Router (ZR) [10].

A WDC would have a functionally distinct description of its resources, as a deterministic set of attributes, as described in [11]. All DCNs and WDCs share a unique pool of resource identifiers, enabling a 1-1 association between what the WDC offers and what the DCN needs. For example, the WDC would offer a camera with a known resolution, bitrate and capturing speed. We assume that a table containing all these identifiers and descriptors are known by the application governing the operation of the network, and each functional identifier would have a reference number. This is communicated by the DCN to its neighboring DCNs.

A WDC intrinsically serves neighboring DCNs, thus it needs to broadcast its availability periodically. While this operation is detailed in Section IV, it is important to note that WDCs will switch to a dormant state when it serves no DCNs, with wake-up timers enabling it to probe DCNs again via a range-limited broadcasted "join" message.

D. *Remote wake-up*

Generally, sensing nodes are deemed useless when their batteries die. Thus, maintenance protocols in WSNs aim to replace their functionality by introducing new ones, or leveraging operation via high-density deployments to start with. In our DWSN paradigm we incorporate an important advancement in utilizing RFID systems. Recent advances in RFID systems, especially semi-passive ones, enable tags to store a small amount of data (typically 56 bytes), and report it back when interrogated by readers.

As such, we cater for the capability of high-end DCN designs to hold short-range RFID readers. Similarly, for WDCs to be equipped with semi-passive tags that could store aggregated information before it runs out of battery. As such, after a WDC loses communication with its neighboring DCNs it would switch into operate and store mode. Thus, enabling a DCN with reader capabilities to interrogate it at a later time when it is in range, and extract information that has been stored over time. We dub the WDC as "proactive" in its former state, and refer to it as "dormant" after it drops in battery power and transfers to the latter state.

IV. DWSN IN OPERATION: THE SYNERGY OF DYNAMIC SENSING

A core motivation for DWSN is the overarching synergy in its operations. The notion of a single-application WSN no longer holds prospect, nor does that of static functionality. More importantly, associations of nodes to functional components require a dynamic paradigm to improve resilience and service delivery on the long run.

A. *Operation of DWSN*

As in any WSN, there is a mandate for a functional description of an application. That is, functional requirements with spatial and temporal mandates, and pre-determined QoS measures. In DWSN we adopt the functional descriptors of application requirements as detailed in [12]. In addition, DCNs and WDCs have pre-determined resources that are static in their attributes. For example, a DCN would have a transceiver, with predefined specifications at known dB levels, power consumption at each level, data rate, protocol stack, etc.

Thus, mapping a functional requirement from an application to the known resources in the network is a sheer assignment problem. In DWSN we establish the architecture that realizes this assignment, and the interactions of the components that render its dynamic functional capabilities.

B. *DCN in operation*

DWSN operates with a non-empty set of DCNs with known locations (to the sink). Each DCN has a static set of attributes. After deployment, and depending on the locations of each DCN, the sink would assign to each DCN its set of functional requirements to be carried out in its region. Since we adopt a homogeneous operation for DCNs, the remainder of this subsection refers to a single DCN in operation WLOG.

Upon receiving the set of functional requirements, each DCN probes its own local resources to match the request. If local resources suffice, it settles for that and transition into operation mode. That is, performing its functional requirements. If not, it probes neighboring WDCs.

This mandate elicits a significant edge in the design of DWSNs. That is, the sink assigns tasks based on location, and DCNs decide in a decentralized fashion the optimal assignment of neighboring resources to their respective functional requirements. Thus, the sink need not encompass global knowledge of the viable resources in the network, only the locations of current DCNs. Hence, if a shortage of resources arises, all the application would require is deploying WDCs in the regions of interest, and their governing DCNs would attach to them and resume operation. Moreover, if functional requirements change, this is a decentralize method for assessing precise need for resources, instead of random dense deployments.

C. *WDC in opertation*

The operation of WDCs is a major contributor to the dynamic dimension of DWSNs. A WDC is placed at the time of network deployment to meet initial functional requirements, and re-introduced later on to mitigate failures and leverage new application requirements. As such, WDCs play an important role in the total resource pool of the network, enabling multi-applications to run concurrently.

The density of WDCs is incremented by new deployments or reduced by failures. The duty of a WDC is to serve neighboring DCNs. Upon deployment, it would broadcast its availability via a Join message announcing how many more DCNs it could serve, and the remaining time it would spend in the "proactive" state. Both metrics are broadcasted to allow DCNs in arbitrating WDC selection should more than one WDC respond.

Each WDC has a cap on operational connections with governing DCNs. When the cap is met, it no longer broadcasts availability until (at least) one of these connections is dropped. After all connections are released, the WDC switches to a dormant state of sense and store, at an increasing sleep timer till it is depleted, or await in a passive wakeup mode if it is equipped with a remote wakeup module.

D. *Resilience model*

Any component in the DWSN is prone to failure. We define failure as the inability of a component to adhere to its functional requirement. For example, an MCU that ran out of memory thus could no longer process data (due to failed memory module, failing bus, etc). It is important to note that in both types of failures, intermittent and permanent, the network is designed to adapt its functionality through periodical re-assignments of tasks to components/resources.

V. CONCLUSIONS AND PARADIGM INSIGHTS

We presented a paradigm that caters for a dynamic approach for WSNs. With a growing abundance of wireless technologies that enable sensing and communication, and interact over multiple access mediums, it is imperative to re-assess our view of what a WSN is. In the near future, most sensing applications, especially in urban settings, will not rely solely on dedicated and overpriced WSNs. In fact, sensing systems provided by smart vehicles and smartphone are already changing our view of WSN capabilities. However, a major hindrance in these technologies is their isolated operation.

DWSN enables nodes to change their functional mandates post deployment, enabling a WSN that can change its application span over time. We contend that the presented DCNs will be easily replaceable with smartphones, and WDCs will evolve from resources offered by a myriad of wirelessly enabled devices. We realize a true opportunity for synergy, and hence presented this paradigm to shift the operation of WSNs from isolated progression. Thus, metrics governing WSN operation towards synergy are network deployment cost (initial and maintenance), resilience to failures (intermittent and permanent) and operational longevity.

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