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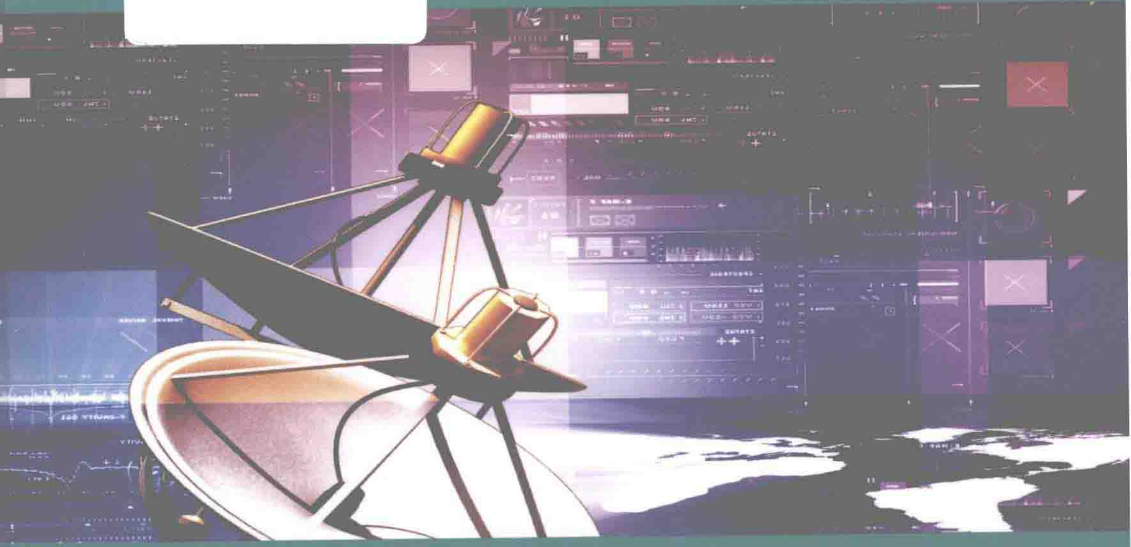

Dynamic Wireless Sensor Networks

Sharief M. A. Oteafy
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Dynamic Wireless Sensor Networks

To my father, Dr. Mohamed Atef, with much love.

Sharief

To my loving family.

Hossam

Preface

The rapid evolvement of telecommunications has created a significant drift in views and definitions. Desperate attempts at defining systems in this domain have often yielded either vague or sparse statements. This is especially true of wireless sensor networks (WSNs), which are the subject of this book.

Instead of listing what WSNs are and what they are not, we emphasize an alternative to dated and stalled definitions. This book adopts a progressive view of what WSNs encompass and represent, and their evolvement and dependence on different research domains from their realization, to this date, and the projected future.

In our pursuit to summarize substantial research domains contributing to WSN literature, we assume some liability in background for this book's readership. Although the emphasis of this book is presenting self-explanatory topics, it is important to note that a background in telecommunications is of significant aid. The material of this book is non-introductory, and is not typical of undergraduate courses.

Having said that, we address researchers and practitioners alike. The impact and growth of WSNs is evident in everyday technologies. The disparately growing literature of ten places all interested parties in a state of confusion. As a technology, WSNs were primarily developed under an application-specific tailoring paradigm. Recent efforts to generalize their application and standardize approaches in design and maintenance have yielded significant compatibility issues. More importantly, the practitioner today is often faced with contradicting designs and results, so that resorting to application-specific practices seems the only reasonable alternative.

In this book, we adopt a modular approach in understanding the evolution of WSNs, and how different technologies have aided and advanced the current status quo. More importantly, we draw upon current trends and manifestations of WSN literature, to project the future of sensing systems at large; especially as we move into an era of the Internet of things (IoT) and information centric networks (ICNs).

As such, this book is organized to progress with readership through this evolution track, to present a chronological order for advancements and technologies impacting WSNs. The book is organized into three core components. Namely, introduction and evolution, co-existing and potentiating technologies, and finally an encompassing dynamic resource reuse paradigm. We conclude this book with a chapter dedicated to the most promising future outlooks in WSN development; most notably in synergy with the prominent tides of IoT and ICNs.

List of Acronyms

BAN	Body Area Network
BLE	bluetooth low energy
BMI	brain-machine interface (in control of dynamic prosthesis)
CSMA	carrier sense multiple access
CSMA/CA	carrier sense multiple access/collision avoidance
dB	power relative to 1 mW (for RF transceivers)
DCN	dynamic core node
DLNA	digital living network alliance
DTN	delay tolerant network
DWSN	dynamic wireless sensor network
FPS	frames per second (for a camera)
GPS	global positioning system
ICN	information centric networks (also known as CCN)
IETF	Internet Engineering Task Force
INS	inertial navigation system
IoT	Internet of Things
IPv6	internet protocol (IP) version 6 (replacing IPv4)
LoS	line of sight
LP	linear programming
MANet	mobile *ad hoc* network
MCU	micro-controller unit
MEMS	micro electro-mechanical systems
MILP	mixed integer linear programming

MTTF	mean time to failure (mean uptime of system)
MULE	mobile ubiquitous LAN extensions
OAP	over the air programming (of SNs)
P2P	peer to peer (network communication)
PoF	potential functions (in RR-WSN)
QoR	quality of resource
QoS	Quality of Service
ReP	resource pool (in RR-WSN)
RFID	radio frequency identification
RR	resource reuse
RR-WSN	resource reuse – in wireless sensor networks
RSSI	received signal strength indicator
Rx	receiver/receive
SLA	service level agreement
SN	sensor node
SODA	service-oriented device architecture (SODA)
Tx	transceiver/transmit
ULS	ultra large scale
VH	vertical handoff (over wireless access technologies)
VoR	value of resource
WASN	wireless actuator sensor network
WDC	wireless dynamic component
WMSN	wireless multimedia sensor network
WSN	wireless sensor network
ZED	ZigBee end device (under a ZigBee protocol stack)
ZR	ZigBee router (under a ZigBee protocol stack)

List of Notations

Symbol	Description	Type
F	All functional requirements for network	
A	Set of applications to run on network	
R	All resources in network	$\mathbb{N}$
N	All nodes in network	$\mathbb{N}$
$\boldsymbol{n_i}$	Node $\boldsymbol{i}$, where $0 \leq i \leq \lvert N \rvert$	$\mathbb{N}$
$\boldsymbol{R_i}$	Total resources in node $\boldsymbol{n_i}$	$\in ReP$
$\boldsymbol{\Theta_i}$	Set of resource classes in node $\boldsymbol{n_i}$	$\in ReP$
$\boldsymbol{r_{i,n}}$	n^{th} resource class in $\boldsymbol{R_i}$	$\in ReP$
$\boldsymbol{r_{i,n}^k}$	k^{th} instance of resource $\boldsymbol{r_{i,n}}$	$\mathbb{N}$
$\boldsymbol{F_j}$	set of functional requirements for $\boldsymbol{a_j}$, where $0 \leq j \leq \lvert A \rvert$	$\in PoF$
$\boldsymbol{f_{j,m}}$	m^{th} functional requirement in $\boldsymbol{a_j}$	descriptor
$\boldsymbol{\Psi}$	A set of tuples of assigned functions to resources $\boldsymbol{f_{j,m}} \rightarrow \boldsymbol{r_{i,n}^k}$	
$\boldsymbol{\gamma_{i,\alpha}^{\beta}}$	Functional energy impact of using resource $\boldsymbol{r_{i,\alpha}^{\beta}}$	$\mathbb{R}^+$
$\boldsymbol{\phi_i}$	Nodal cap of resources used	$\mathbb{N}^+$
$\boldsymbol{d_{i,\alpha}}$	Duty cycle of resource class $\boldsymbol{r_\alpha}$ in node $\boldsymbol{n_i}$	$\mathbb{R}^+$
$\boldsymbol{\theta_{i,\alpha}}$	Power consumption of resource class $\boldsymbol{\theta_\alpha}$ in node $\boldsymbol{n_i}$ in mW	$\mathbb{R}^+$

$\boldsymbol{\varepsilon_i}$	Energy reservoir at node $\boldsymbol{n_i}$ (remaining)	$\mathbb{R}^+$
$\boldsymbol{\delta_{i,\alpha}}$	Portion of energy allocated for resource class $\boldsymbol{r_\alpha}$ in $\boldsymbol{n_i}$	$\mathbb{R}^+$
$\boldsymbol{B_\alpha}$	Arbitrator in region $\boldsymbol{\alpha}$	
$\rho(R)$	Total set of resources in current ReP, i.e., $\cup_{\forall i} \boldsymbol{R_i}$	
ReP_α	Current resource pool for arbitrator $\boldsymbol{B_\alpha}$	
$\lvert\boldsymbol{\Theta_v}\rvert$	number of resources in current ReP of type $\boldsymbol{v}$	$\mathbb{N}^+$
$\boldsymbol{V^R}$	Set of vertices representing resources in current ReP	
$\boldsymbol{V^F}$	Set of vertices representing functional requirements in current ReP	
$\boldsymbol{\tau_t}$	Duration of round $\boldsymbol{t}$	$\mathbb{R}^+$
$\boldsymbol{v_{st}}$	Sojourn time of resource $\boldsymbol{v}$ in network vicinity	$\mathbb{R}^+$
$\boldsymbol{v_{DC}}$	Duty cycling of resource $\boldsymbol{v}$ while in network vicinity	$\mathbb{R}^+$
$\boldsymbol{v_{et}}$	Effective time of a transient resource in network vicinity	$\mathbb{R}$
$\boldsymbol{\kappa(v)}$	Cost of utilizing resource $\boldsymbol{v}$	$\mathbb{R}$
$\boldsymbol{\omega_f}$	Weight factor for functional impact on round duration	$\in [0,1]$
$\boldsymbol{\omega_c}$	Weight factor for cost impact on round duration	$\in [0,1]$
$\boldsymbol{\acute{C}_r}$	Normalized network valuation of resource with cost $\boldsymbol{C_r}$	$\mathbb{R}$
$\boldsymbol{\alpha_r}$	Weight factor of $\boldsymbol{\acute{C}_r}$ valuation on elastic pricing of $\boldsymbol{C_r}$	$\mathbb{R}$
$\boldsymbol{\epsilon_i}$	Normalized indicator of depleted energy at node $\boldsymbol{n_i}$	$\in [0,100]$
C_r^{max}	Asymptotic limit of valuation for resource $\boldsymbol{C_r}$	$\mathbb{R}^+$
s_r	Rate of increase in valuation of a resource	$\mathbb{R}^-$

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1

Evolution of Wireless Sensor Networks

"What a heavy burden is a name that has become too famous"

– Voltaire

We have come quite far since cavemen utilized fire to detect lions approaching their caves. Fire, serving both as a deterrent and a detector (via resulting shadows), was one of man's earliest sensing mechanisms. Thousands of years later, we have the technology to detect traces of pheromones, intrusion of malaria-mosquitoes, send biological sensors down the blood stream and report forest fires by harvesting power from the pH imbalance surrounding tree roots[1]. Not long after the emergence of wireless networks, practitioners integrated wireless tethering to deliver sensing into regions never thought possible; both in the extremities of the Earth, and within our own bodies.

Wireless sensor networks (WSNs) have evolved from many domains and due to various application demands. Today, the view of "what a WSN comprises" differs significantly, and is almost always a function of the domain of interest. Thus, WSN definitions are generally either vague or non-inclusive. It is misleading to tie definitions to WSN predecessors without context.

In this chapter we begin our journey with WSNs from their establishment, to current norms and commonalities in design. Hence, we address a developmental view, based on chronological advancements in telecommunications. Understanding what a WSN is, and the static nature of its initial propositions and design

1 Even this is quite dated research, published by scientists from MIT [LOV 08a].

parameters, opens the door for the discussion of novel paradigms in WSNs; namely the topic of this book. We focus our discussions on paradigm shifts that render WSNs dynamic, both in operation and utility.

1.1. The progression of wireless sensor networks

First, it is important to note the static nature of many of the early designs and deployments of WSNs. In the mid-1990s the rise of mobile *ad hoc* networks (MANets) caused a stir in communications research and industry. Simply, being able to construct and utilize a wireless network on the go, without establishing a fixed topology or tending to its operation frequently, struck practitioners in this domain with significant ideas for advancements. A detailed overview of MANets and their pertinent challenges was presented by Chlamtac, Conti and Liu in [CHL 03]. Integrating MANets with sensors lead to the development of WSNs by the late 1990s.

The diversity of assumptions made on what a WSN comprises, resulted in a wide range of architectures that are dubbed sensor networks. However, they mostly maintain a number of properties; namely wireless communication, coordinated operation and reporting to sink(s). An intrinsic umbrella is to maintain energy efficient operation in all WSN protocols.

As WSN architectures and protocols evolved, their tasks extended beyond sheer reporting. Their complexity expanded many folds in the events to be detected, redundancy in reporting required, density of deployments, quality of data, coverage span and reliability. Significant control overhead resulted from mandating coordination, especially when driven by attempts to synchronize sensor node operation. More importantly, the advent of real-time sensing applications mandated that WSNs operate reliably under significant constraints of time and power consumption. A comprehensive survey on synchronization problems in WSNs is presented in [SUN 05] and highlights how a single requirement can significantly impact operational mandates of a WSN and increase its overhead without improving the quality of the data collected.

As our requirement for WSN coverage and geographical span grew, single-hop communication with the sink became impractical. The simple task of sensing and reporting – over multi-hop – resulted in bottlenecks of energy dissipation and time latency issues, demonstrated in Figure 1.1.