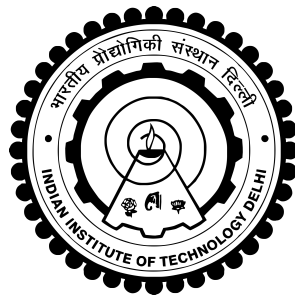


DISTRIBUTED DATA-GATHERING PROTOCOLS IN AD-HOC WIRELESS NETWORKS

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JULY 2019

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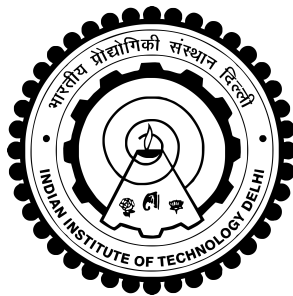
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Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



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Certificate

This is to certify that the thesis titled “**Distributed Data-Gathering Protocols in Ad-hoc Wireless Networks**”, submitted by **Vijay Arvind Rao**, to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any Degree or Diploma.

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Vijay Arvind Rao

Abstract

The design and choice of routing protocols in wireless sensor networks is critical as it affects performance, lifetime and scaling. Wireless sensor networks are primarily used to gather sensor data. The efficiency of the communication protocol used to move sensor data from the nodes to the sink, determines the performance of the network (in terms of battery-life and data-reliability). Three approaches have been proposed, analysed and implemented on hardware to achieve higher efficiency in the routing of sensor data in wireless networks.

We have designed, built and used the Pratham node, an embedded platform with programmable wireless communication range and Over-The-Air programming capability. It is a new design for wireless node hardware aimed at creating a class of heterogeneous sensor networks which bridge the gap between ultra-low power short range and high power long range wireless sensor nodes, while maintaining ease of use and robustness of software. The wireless link created by Pratham nodes is characterized for throughput, quality and power profiles for elementary operations. The supported Over-The-Air programming process is modelled as a Colored Petri Net to analyse its performance. Typical network lifetimes are discussed and the effect of post-deployment remote programming on the life of the node is calculated.

We also developed a novel communication protocol - Adaptive Transmission Power Protocol - for Wireless Sensor Networks with the facility of re-configuring the transmission power of the hardware. We have described the specifications of the protocol including the packet format and the contention avoidance methods. This protocol was implemented on Pratham nodes and the performance was evaluated for fundamental operations. An additional method to assess the performance of the hardware with regard to the transmission power level was analysed. The results show that non-overlapping regions exist for different transmission power levels where the system performance is optimum. More importantly, these regions move farther from the node with increase in transmission power level. This proves using both, simulation and a hardware test-bed, that re-configuring transmission power levels is an effective way of

saving energy in Wireless Sensor Networks.

We present a novel approach to collect data in sensor networks. In our proposed protocol, the routing of data is controlled by a special packet - the Operator Packet. This Operator Packet circulates through the network (a) allowing nodes to report data when they need to and (b) is circulated preferentially to nodes with more data and with higher residual battery levels. The circulation algorithm presented in this chapter takes $O(n)$ time. It creates an opportunistic routing condition – the nodes operate only if their battery levels permit. This leads to controllable lifetime, with average lifetimes of upto 99% of the preconfigured target lifetimes. If nodes in the network are configured with similar target lifetimes, a highly synchronized network death is possible. The end-user can configure devices to operate for a desired lifetime and achieve reliable operation for that duration—this is the motivation behind the development of this protocol. Compared to the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol and Hybrid Energy Efficient Distributed clustering protocol (HEED), the proposed protocol achieves higher lifetimes (60% of LEACH and 165% of HEED respectively) and improved Coefficient of Synchronous Death (17% of LEACH and 102% of HEED respectively). We have also suggested a corrective method to reduce data drops in field deployments.

We propose a novel communication protocol for gathering data with increased efficiency. The novelty of this protocol is in enabling prompt automatic switching between beaconing-mode (which consumes extremely low power) and relaying-mode (which requires higher amount of power for setting-up and maintaining routes). The concept is bio-inspired by the ‘murmuration’ behaviour of starlings – a natural phenomenon observed in flocks of birds in flight. The proposed protocol is an improved implementation of the Bellman-Ford Algorithm and manages to mitigate the formation of loops using the novel murmuration inspired algorithm. Through simulation, we show that the protocol performs well when the network size is scaled and is also effective in extending the lifetime of the network. A hardware implementation has also been presented to validate the feasibility of the protocol in real world setups.

सार

तार रहित (वायरलेस) संवेदना उपकरण (सेंसर) सम्पर्क संजाल (नेटवर्क) में अनुमार्गण (राउटिंग) तरीके (प्रोटोकॉल) की रचना और चुनाव महत्वपूर्ण हैं क्योंकि यह उपकरणों के निष्पादन, प्रयोग अवधि और क्षमता बढ़ाने की सम्भावना को प्रभावित करते हैं। वायरलेस सेंसर नेटवर्क मुख्य रूप से सेंसर उपकरणों से जानकारी को (डेटा) इकट्ठा करने के लिए इस्तेमाल किए जाते हैं। जिस राउटिंग प्रोटोकॉल का उपयोग नोड से सिंक तक सेंसर डेटा को स्थानांतरित करने के लिए किया जा रहा हो, उसका निष्पादन-कुशलता नेटवर्क के प्रदर्शन (बैटरी-उपयोग-दर और डेटा-विश्वसनीयता के संदर्भ में) को निर्धारित करता है। इस थीसिस में वायरलेस नेटवर्क में सेंसर डेटा के राउटिंग में उच्च दक्षता प्राप्त करने के लिए तीन दृष्टिकोण प्रस्तावित किए गए हैं और इनका विश्लेषण एवं हार्डवेयर कार्यान्वयन किए गए हैं।

हमने 'प्रथम' नामक नोड को निर्मित और उपयोग किया है। इस नोड की वायरलेस संचार पहुंच प्रोग्राम द्वारा बदली जा सकती है। इस में 'ओवर-द-एयर' प्रोग्रामिंग की भी काबिलियत है। यह वायरलेस नोड हार्डवेयर के लिए एक नया डिज़ाइन है जिसका उद्देश्य विषम सेंसर नेटवर्क का एक वर्ग तैयार करना है जो सॉफ्टवेयर की उपयोग और मजबूती में आसानी बनाए रखते हुए न्यूनतम पावर वाले कम रेंज और ज्यादा पावर वाले लम्बे रेंज वायरलेस सेंसर नोड के बीच में हो। 'प्रथम' नोड द्वारा बनाया गया वायरलेस लिंक प्राथमिक कार्यों के लिए थ्रूपुट, गुणवत्ता और पावर प्रोफाइल के लिए उपयोग किया गया है। ओवर-द-एयर प्रोग्रामिंग प्रक्रिया के निष्पादन कुशलता का विश्लेषण करने के लिए एक पेट्री नेट तैयार किया गया है। विशिष्ट नेटवर्क जीवन काल पर चर्चा की गयी है और नोड के जीवन पर तैनाती के बाद के दूरस्थ प्रोग्रामिंग के प्रभाव की गणना की गयी है।

हमने हार्डवेयर के वायरलेस संचार पावर को निष्पादन के दौरान बदलने की सुविधा के साथ वायरलेस सेंसर नेटवर्क के लिए एक नया संचार प्रोटोकॉल - एडेप्टिव ट्रांसमिशन पावर प्रोटोकॉल भी विकसित किया है। हमने पैकेट प्रारूप और विवाद से बचने के तरीकों सहित प्रोटोकॉल के विनिर्देशों का वर्णन किया है। इस प्रोटोकॉल को 'प्रथम' नोड पर लागू किया गया है और उसके निष्पादन का मूल्यांकन किया गया। संचार पावर स्तर के संबंध में हार्डवेयर के प्रदर्शन का आकलन करने के लिए एक अतिरिक्त विधि का विश्लेषण किया गया। परिणाम बताते हैं कि विभिन्न ट्रांसमिशन पावर स्तरों के लिए गैर-अतिव्यापी क्षेत्र मौजूद हैं जहाँ सिस्टम का निष्पादन इष्टतम है। इससे भी महत्वपूर्ण बात, ये क्षेत्र संचरण पावर स्तर में वृद्धि के साथ नोड दूर पाए जाते हैं। यह सिम्युलेशन और हार्डवेयर प्रयोगों

के द्वारा यह साबित करता है कि संचार पावर स्तरों को निष्पादन के दौरान बदलना वायरलेस सेंसर नेटवर्क में ऊर्जा की बचत का एक प्रभावी तरीका है।

हम सेंसर नेटवर्क में डेटा एकत्र करने के लिए एक नया दृष्टिकोण प्रस्तुत करते हैं। हमारे प्रस्तावित प्रोटोकॉल में, डेटा के राउटिंग को एक विशेष पैकेट - ऑपरेटर पैकेट द्वारा नियंत्रित किया जाता है। यह ऑपरेटर पैकेट नेटवर्क के माध्यम से प्रसारित होता है (अ) नोड को डेटा की रिपोर्ट करने की अनुमति देता है जब उन्हें ज़रूरत हो (ब) इस पैकेट को नेटवर्क में डेटा और अवशिष्ट बैटरी स्तरों के मुताबिक परिचालित किया जाता है। इस अध्याय में प्रस्तुत संचालन एल्गोरिथ्म में $O(n)$ समय लगता है। यह एक अवसरवादी रूटिंग स्थिति बनाता है - नोड केवल तभी संचालित होते हैं जब उनकी बैटरी का स्तर अनुमति देता है। यह करने से जीवनकाल नियंत्रित किया जा सकता है, जिसमें पूर्व-निर्धारित लक्ष्य जीवनकाल के 99% तक के औसत जीवनकाल प्राप्त हो पाते हैं। यदि नेटवर्क में नोड समान लक्ष्य जीवनकाल के साथ कॉन्फ़िगर किए गए हैं, तो अत्यधिक सिंक्रनाइज़ नेटवर्क मौत संभव है। अंत-उपयोगकर्ता इष्टतम जीवन के लिए संचालित करने के लिए उपकरणों को कॉन्फ़िगर कर सकता है और उस अवधि के लिए विश्वसनीय संचालन प्राप्त कर सकता है - यह इस प्रोटोकॉल को बनाने का मकसद है। कम ऊर्जा अनुकूली क्लस्टरिंग पदानुक्रम (LEACH) प्रोटोकॉल और हाइब्रिड ऊर्जा कुशल वितरित क्लस्टरिंग (HEED) की तुलना में, प्रस्तावित प्रोटोकॉल उच्च जीवनकाल (LEACH से 60% और HEED से 165% ज्यादा) प्राप्त करता है और तुल्यकालिक मौत का बेहतर गुणांक (LEACH का 17% और HEED का 102%)। हमने फ़िल्ड परिनियोजन में डेटा के नुस्कान को कम करने के लिए एक सुधारात्मक तरीका भी सुझाया है।

हम ज़्यादा कुशलता से डेटा इकट्ठा करने के लिए एक और नए संचार प्रोटोकॉल का प्रस्ताव रखते हैं। इस प्रोटोकॉल की नवीनता बीकन-मोड (जो बेहद कम बिजली की खपत करती है) और रिले-मोड (जिसमें सेटिंग और रखरखाव के लिए उच्च मात्रा में बिजली की आवश्यकता होती है) के बीच शीघ्र स्वचालित परिवर्तन को सक्षम करने में है। उड़ान में पक्षियों के झुंडों में पाया जाने वाला एक प्राकृतिक घटना - 'मरमरेशन' - से यह प्रेरित है। प्रस्तावित प्रोटोकॉल बेलमैन-फोर्ड एल्गोरिथ्म का एक बेहतर कार्यान्वयन है। 'मरमरेशन' से प्रेरित होने की वजह से यह एल्गोरिथ्म डेटा संचार में अंदरूनी डेटा संचार जाम होने से रोक पाता है। सिम्युलेशन के माध्यम से हम दिखाते हैं कि प्रोटोकॉल अच्छा प्रदर्शन करता है जब नेटवर्क का आकार छोटा होता है और नेटवर्क के जीवनकाल को विस्तारित करने में भी प्रभावी होता है। वस्तुविकतता में प्रोटोकॉल की उपयोगिता को दर्शाने के लिए एक हार्डवेयर कार्यान्वयन भी प्रस्तुत किया गया है।

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List of Abbreviations

ACK	Acknowledgement
ADC	Analog to Digital Converter
AMRP	Average Minimum Reachability Power
AODV	Ad-hoc On-demand Distance Vector
API	Application Program Interface
ATPP	Adaptive Transmission Power Protocol
BFA	Bellman Ford Algorithm
BL	Boot Loader
BLE	Bluetooth Low Energy
BS	Base Station
CH	Cluster Head
COP	Circulating Operator Packets
CP	Clustering Phase
CPN	Colored Petri Net
CSD	Coefficient of Synchronous Death
CSMA-CA	Carrier Sense Multiple Access - Collision Avoidance
dB	decibel
DCL	Data Collection Latency
DGP	Data Gathering Phase
DNS	Domain Name System
DS	Data Sinks
DSDV	Destination Sequences Distance Vector
DSR	Dynamic Source Routing
EAD	Effective Average Degree
EEML	Extended Environments Markup Language
EOD	End Of Data
FlockCC	Flock inspired Congestion Control
FND	First Node Death

FoV	Field of View
FRESH	Fresh Encounter Search algorithm
FS	Free Space
FTP	File Transfer Protocol
GAP	Generic Access Profile
GATT	Generic Attributes
GMMM	Gauss Markov Mobility Model
GPIO	General Purpose Input Output
HBS	Hops to Base Station
HEED	Hybrid Energy Efficient Distributed clustering
HTTP	Hyper Text Transfer Protocol
I2C	Inter Integrated Circuit
IBL	Initial Battery Level
IEEE	Institute of Electrical and Electronics Engineers
IP	Internetworking Protocol
IPv4	IP version 4
IPv6	IP version 6
ISM	Industrial Scientific and Medical
LAN	Local Area Network
LDO	Low Drop Out (Voltage Regulator)
LEACH	Low Energy Adaptive Clustering Hierarchy
LND	Last Node Death
LQI	Link Quality Indicator
MAC	Medium Access Channel
MANET	Mobile Ad-hoc Networks
MEMS	Micro Electro Mechanical Systems
mJ	milli Joule
MP	Multi Path
MTE	Minimum Transmission Energy
MULE	Mobile Ubiquitous LAN Extension
ON	Operator Node
OP	Operator Packets
ORIENT	Opportunistic Relaying in Energy-constrained Networks
OSI	Orientation Stream Index

OTA	Over The Air
PAN	Personal Area Network
PTD	Power Transition Delay
RHEED	Reduced Hybrid Energy Efficient Distributed clustering
ROO	Regions of Optimum Operation
RREP	Route Reply
RREQ	Route Request
RSSI	Received Signal Strength Indicator
SEP	Stable Election Protocol
SMTP	Simple Mail Transfer Protocol
SN	Sensor Nodes / Sensing Nodes
SNMP	Simple Network Management Protocol
SPI	Serial Peripheral Interface
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TSC	Time Since Contact
TSD	Time Since Departure
UART	Universal Asynchronous Receiver Transmitter
UDP	User Datagram Protocol
USB	Universal Serial Bus
WiFi	Wireless Fidelity
WSN	Wireless Sensor Networks
XML	Extensible Markup Language
ZIF	Zero Insertion Force
ZoA	Zone of Attraction
ZoO	Zone of Orientation
ZoR	Zone of Repulsion