Demonstration of a Multi-Interface Multi-Channel Routing Protocol (MMCR) for WSNs using Missouri S&T Motes

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1. Introduction

Typical sensor nodes are equipped with radios that can operate on multiple non-interfering channels. These channels can be utilized for parallel data transmissions thus increasing a network capacity, or to improve resilience against the RF interference and congestions. Traditional sensor networks with a very low duty cycle and minimal data transfer might not need such capabilities. However, more modern, larger applications exceed single-channel capacity either during critical events, or when traffic from numerous sources converges at the sink/monitoring station. One of the demonstrated scenarios include real-time voice-over-WSN communication scenario as illustrated in Figure 1. In such scenarios, the benefits of the MMCR scheme [1] outweigh added complexity. Moreover, the MMCR scheme may be selectively enabled for either the specific time period or part of the network creating a hybrid solution.

The demonstration presents the *novel aspects of the proposed solution* including: (1) real-time, voice communication over random access wireless sensor network; (2) efficient utilization of limited resources in WSNs including low bandwidth, limited memory and energy; (3) novel compression scheme that guarantees low distortion of the sensor signal (data) over a low bandwidth links; (4) efficient, dynamic route and channel switching in WSN in presence of interferences and high traffic.

The MMCR scheme uses a metric defined by a throughput, end-to-end delay and energy utilization to select Multi-Point Relay (MPR) nodes to forward data packets. This protocol minimizes packet losses due to interference. Moreover, the MMCR scheme enables mathematically derived load balancing decisions and channel switching over multiple radio interfaces thus guaranteeing higher throughput and lower delay for congested links in a network.

While the MMCR protocol does not assume a specific physical or MAC protocol, the presented hardware demonstration employs the Missouri S&T Motes with the 802.15.4 radio interfaces. The exhibition scenarios include: (a) rerouting after link failures, (b) channel switching capabilities and (d) load balancing among the available radio channels to avoid the interference and improve performance.

The demonstration setup will include about 20 Missouri S&T Motes in a random topology with two Mote-based headsets for the voice communication and several sensors attached to the selected motes. Further, compression and aggregation are performed to improve the energy savings and network lifetime. The network will be monitored using PC based application to illustrate performance metrics including the collected data, throughput, energy consumption, delay, and jitter. During the demonstration, the implemented features will be disabled and enabled in order to comparatively demonstrate the benefits of the MMCR scheme.

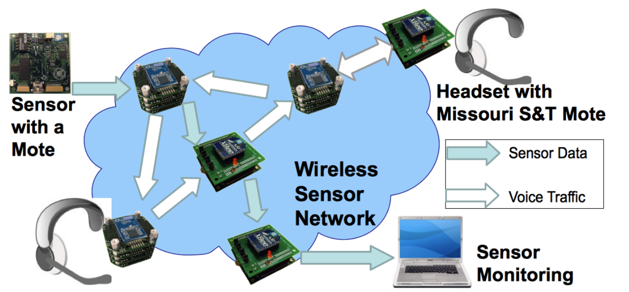

Figure 1. Voice over Wireless Sensor Network Scenario

2. Missouri S&T Motes

Hardware developed at Missouri S&T balances low-power, low-cost, and high performance of both 8-bit (8051-based) and 32-bit (ARM) computing to provide distributed computation, prognostic, and diagnostics abilities to targeted applications. Silicon Laboratories® 8051 based hardware was selected for its ability to provide fast 8-bit processing, low-power consumption, and ease of interfacing to peripheral hardware components. The recently introduced ROLLA Mote is based on ST Microelectronics STM32W chip that integrates an ARM Cortex M3 processor and 802.15.4 transceiver. The new mote provides modern, 32-bit processing capabilities with high energy-efficiency and small form factor. Table 1 summarizes the Missouri S&T hardware models and is briefly discussed next.

2.1 Mote 1: Generation-4 Smart Sensor Node (G4-SSN)

The G4-SSN originally developed at Missouri S&T and subsequently updated at St. Louis University is the main development platform. The G4-SSN extensions include strain gauges, accelerometers, thermocouples, and general A/D sensing. The G4-SSN provides memory and speed advantages over other mote hardware that make it a suitable choice for prototyping where code is not well optimized and includes debugging support.

2.2 Mote 2 – Instrumentation Sensor Node

The Missouri S&T Mote 2, also called an Instrumentation Sensor Node (ISN) is used for interfacing

* Corresponding author: Maciej Zawodniok mjzx9c@mst.edu, 133 Emerson Hall, Missouri S&T, Rolla, MO 65409, USA. Phone: (573)-308-2319
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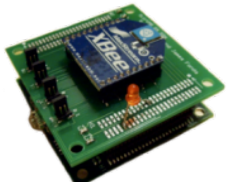
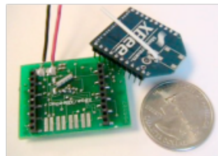
Table 1. Summary of Missouri S&T Motes

	 **Mote 1**	 **Mote 2**	 **Mote F1**	 **ROLLA Mote**
Design	Stackable layers	Miniaturized sensor node	Integrated, multimodal sensors mote	Modular mote with ARM Cortex M3
Intended usage	Development and prototyping; app. with high processing	Simple sensing applications with very light processing	Plug-and-play monitoring (civil infrastructure)	On-the-fly analog signal conditioning Multi-interface radio configuration
Size	Layers: 2"x2" squares with 0.5" interlayer spacing	Roughly the size and weight of a quarter coin	Single 2"x2" layer with add in sensors	1.5" diameter modules
Memory	*Code*: 128 KB; *RAM*: 8448 B; Flash card up to 1GB (CF/SD)	*Code*: 16 KB; *RAM*: 1280 B;	*Code*: 64 KB; *RAM*: 4608 B; SD flash card +64GB; non-volatile FRAM	*Code*: 128 KB; *RAM*: 8 KB; SD flash card +64GB Direct Memory Access (DMA)
Peak Power Consumption	105mW at 3V (2xAA)	21mW at 3V (2xAA)	75mW at 3V (2xAA) **Sensor power supply:** +/-5V at 1W	75mW at 3V (including radio) **Sensor power supply:** +/-5V at 1W
Sensing Accuracy	100k samples with **12-bit** accuracy	**200k** samples with 10-bit accuracy	**200k** samples with 10-bit accuracy	**188k** samples with 12-bit accuracy
Processing	Max. 100 MIPS; Math-coprocessor	Max. 25 MIPS	Max. 48 MIPS	Max. 30 MIPS (*32-bit ARM*)
Cost	+1k series at \$50-\$100 (varies)	+1k series at ~\$30	+1K series at ~\$60	(TBD)

sensors to the network. The ISN allows a sensor to be monitored by a small and low-power device that can be controlled by more resource-reach motes. The ISN is capable of being interfaced with several sensor types and can be instructed by control packets to transmit data in raw or pre-processed form.

2.3 Mote F1 – Integrated Smart Sensor Node

The Missouri S&T Mote F1 has been designed to integrate sensors and signal processing capabilities on a single board. The included sensors and sensor interfaces include: 3-axis accelerometer, strain gauge conditioner, and thermocouple with temperature sensor.

2.4 Rolla Mote

The newest ROLLA Mote is a stackable design that employs the ST Microelectronics ARM Cortex M3 processor with integrated 802.15.4 radio. The architecture with common SPI/I2C bus connecting the layers provides a ideal solution for flexible multi-interface radio configuration. Similarly to the G4-SSN mote, the ROLLA mote is capable of interfacing with number of sensors through a growing set of interchangeable layers.

2.5 Missouri S&T Motes' Capabilities

The abilities of the nodes are shown and contrasted in Table 1 The G4-SSN and its new generation, the ROLLA mote, are intended as the main development platform and high-end node, for example aggregating cluster head in WSNs. The ISN is intended to be a 'simple sample and send sensor node' used to interface to devices. In comparison, the F1 Mote balances and integrates the sensing and networking functionality and offers more memory and processing ability than ISN. Next, the MMCR routing scheme is summarized and the demonstration scenarios discussed.

3. MMCR Routing

A multi-interface multi channel routing protocol (MMCR) is proposed in [1]. It selects routes that enhance bandwidth utilization while maximizing energy efficiency and minimizing end-to-end delay. This proactive routing protocol operates independently of a particular scheme for receiver-based channel assignment. The protocol utilizes the concept of Multi-Point Relays (MPRs) similar to [3]. The scheme forwards packets using only the MPR nodes that are a fraction of the all one-hop neighbors. Hence, the routing complexity reduces for the same network size when compared with other pro-active routing protocols. This paper deals with the hardware verification of the MMCR protocol on the Missouri S&T G4 motes [2].

The WSNs typically generate huge amount of heterogeneous data. The propagation of redundant data is costly in terms of system performance and results in energy depletion, network overloading, and congestion. While effective routing improves the packet delivery ratio, other methods for in-network data processing must be employed to reduce the number of messages relayed without much compromise on the fidelity. With the focus shifting towards multimedia sensor networks for surveillance, compression and aggregation techniques [4] [5] [6] are gaining importance every day. A lot of research has been done on developing tailored compression/aggregation techniques for WSNs. An ant colony approach is used for aggregation in [7]. In [8], wavelets are used to achieve data reduction. In this paper, a Nonlinear Adaptive Differential Pulse Coded Modulation-based Compression (NADPCMC) scheme [9] is used for compression and aggregation in conjunction with the multi-channel routing protocol.

3.1 Utilization Metric

Each two-hop path is evaluated in terms of the proposed [1] utilization metric, $U_{sn_2}^{MPR}$. It is calculated for a path from the starting node s toward its two-hop neighbors n_2 through a relay node n_1 as follows:

$$U_{sn_2}^{MPR} = (BF * EU)/D \quad (1)$$

where $BF = B_A / B_S$ is a bandwidth factor between nodes *s* and n_1 (MPR), B_A is an available (free) incoming bandwidth at the n_1, B_S is an expected/requested outgoing bandwidth at the source node s, $E.U. = E_A^{n1} / E_{TX}^{n1 \to n2}$ is the energy utilization between nodes n_1 to n_2, E_A^{n1} is an available energy at the relay n_1 in Joules, $E_{TX}^{n1->n2}$ is an energy used to transmit message from n_1 to n_2, and D is an end to end delay from node *s* to node n_1 in seconds.

The metric optimization will maximize available bandwidth using bandwidth factor and minimize end-to-end delay using delay factor, *D*. Moreover, the metric will maximize the energy utilization term, which is expressed as energy depletion due to transmissions, thus increasing energy efficiency and lifetime of the nodes and network. The utilization factor given by bits per second is a direct measure of the total throughput of the link. Additionally, a route is selected if and only if the bandwidth factor for all the links on the path is greater than one. Consequently, the route associated with a flow guarantees sufficient bandwidth for the requested service.

3.2 MPR selection

The HELLO packets are periodically exchanged among the one-hop neighbors to update the relevant utility factors (1). Once the two-hop neighborhood is discovered, each node uses the information to select multipoint relay (MPR) nodes from the one-hop neighbors to reach all the two-hop neighbors with minimum cost given by equation (1). The MPR selection metric proposed in [1] ensures that the paths through the *MPRs optimize the energy consumption, delay, and bandwidth utilization*. Additionally, the MPR selection algorithm ensures that there is sufficient available bandwidth to support the existing and new traffic flows. The optimal set of MPRs varies with traffic and network congestion.

3.3 Topology discovery and route selection

The selected MPR nodes periodically transmit Topology Control (TC) messages with corresponding link utilization factor data and topology information. Upon receiving the TC messages, each node in the network records the information and proactively computes the routes to all possible destinations.

The route selection iteratively calculates the total cost factor for a route with k intermediate MPRs nodes in the path as follows:

$$C_{s,d} = \sum \left(C_{s,n_2}^{n1}, C_{n1,n_3}^{n2}, ..., C_{n_{k-2},n_k}^{n_{k-1}}, C_{n_{k-1},d}^{n_k} \right) \quad (2)$$

where $C_{s n_2}^{MPR} = 1/U_{s n_2}^{MPR}$ is the cost metric between node *s* and its two-hop neighbor $n_2 \in N^2(s)$ through the relay node n_1 (MPR). Once a route is found to the destination, the availability of multiple, independent channels and interfaces are exploited to perform load balancing for a particular link.

4. Demonstrated Application Scenarios

The primary application demonstrates the real-time voice communication using the 802.14.5 radios, shown in Figure 1. The voice data is compressed using *nonlinear adaptive pulse coded modulation-based compression (NADPCMC)* scheme [9]. Additionally, the sensor data are collected and forwarded along the voice data through the network and presented at the laptop screen. Routing support will be provided by the MMCR protocol and a real-time graphical display of the performance metrics will be shown. Approximately 10-20 nodes will be deployed and interfaced with a PC base-station and results shown via the base-station. Additionally, the application layer will be included to show an example of deployment of the system. As failures are induced in the pneumatic, feedback over the network is given as to the state of the actuator system at the base station.

4.1 Demo Requirements

- A table to accommodate one laptop and few small Missouri S&T Motes (3in x 3in).
- At least one power outlet.
- Poster space/stand

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] Reghu Anguswamy, Maciej Zawodniok and S. Jagannathan, “A Multi-Interface Multi-Channel Routing (MMCR) Protocol for Wireless Ad Hoc Networks,” *Proc. of the IEEE Wireless Communications and Networking Conference*, pp. 1-6, Apr 2009.

[2] James Fonda, Steve Watkins, S. Jagannathan, and Maciej Zawodniok, “Embeddable Sensor Mote for Structural Monitoring,” *SPIE 15th Annual Int’l Symposium on Smart Structures/NDE: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2008*, vol. 6932, pp. 69322V.1-69322V.11, 2008.

[3] A. Qayyum, L. Viennot and A. Laouiti, “Multipoint relaying for flooding broadcast messages in mobile wireless networks”, *Proc. of HICSS*, pp. 3866 – 3875, January 2002.

[4] K. Dasgupta, K. Kalpakis, and P. Namjoshi, “An Efficient Clustering-based Heuristic for Data Gathering and Aggregation in Sensor Networks,” *Proc. Of WCNC*, Vol. 3, 16-20 March 2003.

[5] Krishnamachari, D. Estrin, and S. Wicker, “The Impact of Data Aggregation in Wireless Sensor Networks,” *Int’l Workshop on Distributed Event-Based Systems*, pp. 414 – 415, Jul 2002.

[6] Boulis, S. Ganeriwal, and M.B. Srivastava. “Aggregation in Sensor Networks: An Energy-Accuracy Trade-off,” *Proc. of IEEE Sensor Network Protocols and Applications*, pp. 128 – 138, 2003.

[7] Misra, R., and Mandal, C, “Ant-aggregation: ant colony algorithm for optimal data aggregation in wireless sensor networks,” *Proc. of IFIP Int’l Conference on Wireless and Optical Communications Networks*, pp. 1 – 5, 2006.

[8] Wenyu Cai, Meiyan Zhang, “Data Aggregation Mechanism based on Wavelet-entropy for Wireless Sensor Networks,” *Proc. of WiCOM*, pp. 1 – 4, Oct 2008.

[9] Kasirajan, P., Larsen, C., and Jagannathan, S., “A New Adaptive Compression Scheme for Data Aggregation in Wireless Sensor Networks,” Proceedings of the *IEEE WCNC 2010*.