Matrix Routing – An interference range insensitive routing protocol for Wireless Sensor Networks

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Abstract

Interference ranges can dramatically affect the throughput in wireless sensor networks. While the transmission range defines the maximum physical range of a radio signal the interference range determines the area in which other nodes will be prevented from successful receiving or transmitting signals. In this paper we present an initial self organizing routing protocol for wireless sensor networks, named Matrix Routing, which is maximally insensitive even to high interference disturbances. Matrix Routing is predictable, proactive but not table driven, needs minimum hardware and computational power and does not require transmission of routing packets. The protocol is characterized by zero overhearing costs and minimal idle listening. The paper shows a proof of concept, evaluates potential of our algorithm and discusses strength, limitations and application areas.

1. Introduction

Successful transmission and receiving mainly depends on two aspects – transmission range and interference range [1][3]. Assuming a concentric dissemination, a transmission range constitutes the maximum range where a RF signal can be correctly received. The interference range defines the area where a sending node can disturb a transmission from a third node. While sending ranges mainly depend on the RF propagation function, interference ranges are impossible to foresee, depend on analog RF parameters as strength of signals or reflection and may change frequently. This effect is known from practical implementations and influences data transmission. Fig. 1. shows an example of transmission and interference ranges. For simplicity ranges are depicted concentric which is not necessarily given in physical networks [16].

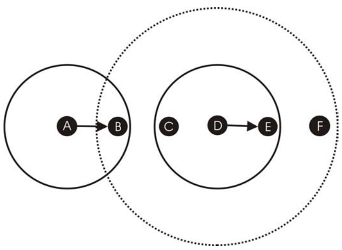

Fig. 1. Transmission and interference ranges in wireless sensor networks. Solid lines denote the valid transmission range, dotted lines depict the interference range. A node between the transmission and interference range will be held from successfully receiving and sending valid signals

Wireless routing requires cooperation of nodes to forward packets through a network. In this paper we focus on typical flat-based routing scenarios [7] where the information will be transmitted to a central station. We will present a TDMA based routing protocol suited for sensor networks with high interference ranges where other approaches fail.

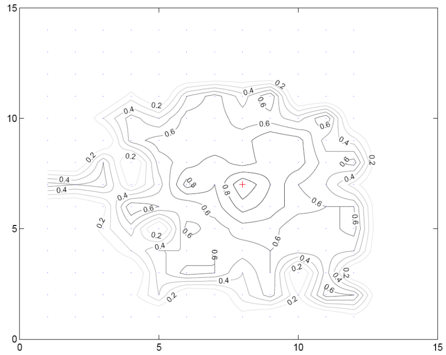

Fig. 2. Contour plot of packet reception and interference area probability for packets generated by a central node [16].

2. Scenario motivation/Interference problem

A typical application case is collection of data in production facilities and supply chains where data are collected by a central station for off-site analysis. Typically, sensor nodes in such networks have low computational power and therefore need routing protocols with low computational overhead. Also, low power nodes do not provide enough memory to store large routing tables. In many industrial scenarios sensor nodes are installed in high density with nodes having short transmission ranges to conserve energy [18]. Together with low sensitivity of the receivers, interference of signals is then a major problem. In many wireless sensor network models, transmission range and interference range are assumed to match, meaning nodes can not disturb each other when not in transmission range. As motivated above, for certain kind of scenarios such a model, and thus routing protocols based on them, are not suitable. We present a first routing method that is completely unaffected by interference with high random nature (section 3), has low administrative overhead and low energy budget for nodes. Note that the proposed protocol is deliberately not optimized towards any other efficiency parameter to study the effect of interference and its countermeasures. This means, we focus on addressing the interference range problem [8][9] only. Modeling the interference characteristics in sensor networks is challenging because RF characteristics of nodes and environments are neither known a priori nor computable due to its stochastic, rapidly changing characteristic. Any protocol working in settings with high interference must assume that interference can happen anytime. Most routing protocols are incapable of dealing with radio channels suffering from high interference ranges and thus have a high interference ratio. In an extreme case, all nodes will be interfered and banned from sending packets if only one of the nodes starts sending and thus stopping many routing protocols from operation. Throughout the paper we discuss these phenomena for some existing and for our proposed routing protocol under various conditions.

3. Related Work / State of the art

Sensor nodes can disturb each other, even if they are far away from successful transmission ranges [5]. Xu et al. further indicate that the interference range can be modeled as a function of distances between source and destination and the physical layer characteristics. This approach is valid for a simplified view on the problem of interference. But as transmission range in general change heavily over time and is difficult to be modeled analytically [17], it can be assumed that interference ranges behave similar. Blake et al. analyzed the interference range problem from channel capacities' point of view [2] indicating a correlation between per node capacity of a sensor network, its size and the interference range involved. Such models are the underlying assumption of the approach in [4], where an Interference Graph is created to improve the throughput. With the help of an Interference Graph each node knows which pairs of communication will interfere. While this improves network throughput, the Graph needs to be created and stored somewhere which requires network traffic and creates computational overhead. Also, Interference Graph based methods are not a good solution when frequent changes of RF channel behaviour are expected.

Routing algorithms in Wireless Sensor Networks can be classified in flat, hierarchical and location based routing [6][7]. For the proposed small-scale settings above, both hierarchical routings and location based routings are not appropriate. We will focus our discussion on flat based routing protocols, where Matrix Routing can be classified. Typical examples are SPIN [8][9], Direct Diffusion [10], Minimum Cost Forwarding Routing Algorithm [11], COUGAR [12] and ACQUIRE [13]. In Direct Diffusion techniques, sensor nodes maintain a set of path information. In our scenario we do not have the amount of memory available that is necessary to store routing tables or path information. Well suited protocols for wireless sensor networks are: Real Time Search (e.g. SPEED [19]), Constrained Flooding [20], Spanning Tree [21] and Adaptive Tree [22].With SPEED He et al. proposed a real time routing protocol for wireless sensor networks especially tailored to be stateless and minimizing the control overhead [19]. SPEED is highly efficient where node density is high and resources of each node are rare. These attributes attracted our attention in interference range scenarios. With Constrained Flooding Zhang et al. proposed a promising approach which takes robustness advantages from flooding but maintains energy efficiency by constraining retransmissions [20]. We analyze the robustness of Constrained Flooding against high interference ranges in our simulations. A proactive approach is provided by England et al [21]. Their Spanning Tree protocol aims robustness using a proactive approach withstanding disturbances and exhibits good performance. It is well suited for data collections in sensor networks and its throughput is thus compared with Matrix Routing in interference range scenarios. Finally we analyze the Adaptive Tree protocol – a routing algorithm focusing on routing data to a base station [22]. With this algorithm Zhang et al. present an adaptive routing mechanism, using real-time reinforcement learning strategies. We consider these four algorithms as the most promising routing protocols to deal with the interference range scenario. We analyze and show comparison to Matrix Routing (section 5) and indicate that Matrix Routing is superior if interference range reaches a certain threshold.

4. Matrix Routing Concept

Matrix Routing uses TDMA [1] as a basic method to control both access to the channel and to assign routing slots. While TDMA handles interference problems very well, common TDMA approaches do not fit to our demands because it requires every node involved in the negotiation process to be in transmission range. On the other hand, TDMA methods are useful for saving energy: Having each time slot reserved for a certain node, sending/reception time slots – and therefore sleeping time slots – are completely predictable. The name Matrix Routing goes back to the notion to depict the protocol, not from the actual stored information in the nodes. In fact, knowledge is distributed among all participating nodes, requiring only very limited information to be store by each node. The protocol can best be explained using a n x n-matrix, where n is the number of sensor nodes involved. We further refer to the columns as slots and the rows as frames. In each slot a node transmits its information to the network. A node with the slot number a+1 picks up the message and sends it out to eventually reach the base station. The final slot in each frame is reserved for the base station. Any node only requires to remember its sending slots only. After an initialization process a sensor node proceed as follows.

Sensor nodes can serve as sender and router for other packets respectively. Packets are not assumed to be piggy-backed to ensure very short slots fitting only one small packet. Any node has a list of several assigned sending slots. The node wakes up one slot before its sending slot and listens to the channel. If the channel is idle the node sends its packet on the assigned sending slot. If the slot is found to be occupied by a packet, it switches to routing mode and forwards the packet in the assigned slot. Any node may have assigned several slots for routing packets, and one slot for sending own sensor data. This "own" sending slot is assumed not to be preceded by a packet from another node. If this is the case – e.g. because a new node enters the network - a new sending slot is needed because the former sending slot now acts as a routing slot.

The following example explains the initialization process in more detail. In initial state each node only knows the size of the matrix. Minimum matrix size is given by the number of nodes. In practical settings we recommend to oversize the matrix to be prepared for additional nodes. Initially, a node needs to find a sending slot. It listens to the channel at least one complete matrix cycle. For an example run, let us assume the topology in Fig. 3. and the matrix in TABLE I. Assume the first node to enter the network would be node no. 2. No.2 listens on the channel and detects multiple empty slots in front of the master concluding that nobody occupies theses slots. It chooses frame 1/slot 3 as its own sending slot (TABLE I). Now No.3 enters the network with no direct link to the master. No.3 listens one cycle and detects the slot in front of No.2 as empty. The only node it receives data from is No.2 and thus identifying frame 1/slot 2 as sending slot. This way No.2 lost its sending slot for sending own data. If it wakes up at the predefined time slot it detects a packet on slot 2/frame 1, switches to routing mode and remains awake to find a new sending slot resulting in the matrix shown in TABLE I. To obtain a new sending slot the node listens a complete cycle and determines one of the remaining slots in the matrix.

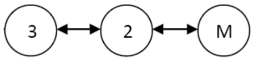

Fig. 3. Example topology

TABLE I. MATRIX AFTER TWO NODES HAVE ENTERED THE NETWORK

Slot 1	Slot 2	Slot 3	Slot 4	
	3	**2**	**M**	Frame 1
		2	**M**	Frame 2
			M	Frame 3

We conserve energy by making nodes switch off their RF unit if they are not assigned to a sending slot. To reduce energy consumption in the initialization phase where lots of nodes compete for a sending slot and prevent collisions we added exponential back off like in CSMA/CA [23] to the initialization procedure. So far we assumed a simplified model to explain the Matrix Routing concept. E.g. we assumed bidirectional links between the nodes involved, which is not necessarily given. We also did not address how to deal with the hidden terminal problem [15]. If two nodes see the same slot as empty and do not recognize each other, their packets may collide. Finally we need to clarify the impact of node failure. All these problems can be solved with MR in very elegant way, by just extending the protocol with some new features: A node having sent its packets stays additionally awake for the following slot allowing any node to hear one slot after sending its packet and thus implicitly checking if the data is received and forwarded correctly by the next node in the frame; this procedure is known as implicit acknowledgement. Failures from a unidirectional transmission and hidden terminal problem lead to acknowledge transmission errors. Thus, node failures can be detected with this procedure as well. If a node fails (e.g. due to battery power drain) all routes through this node need to be reconfigured. Nodes suffering from the failures will detect a transmission failure, set a counter and start reconfiguring if the same slot is missing τ times in a row. We define τ as a time to live (TTL) counter. In practical setting and in section 5 the value is chosen as τ=5.

Memory consumption of Matrix routing for each node is very low: Assuming the network size is less than 256 nodes 1 Byte is necessary to identify slots, frames and number of nodes: the matrix size (nxn matrix, 1 Byte), the sending slots, including slots where nodes act as router. The number of sending slots directly depends on topology with an upper limit given by 2n Bytes and the TTL counter. Thus Matrix Routing memory requirements for each node is limited to 2n+k+1 Bytes.

5. Simulations

We proved the functionality with the MATLAB based simulation environment "Prowler" [14]. System behaviour is implemented and tested against various typical topologies. We analyzed a rectangular topology containing 25 sensor nodes and a transmission area defined by P(x)=1/(1+x^2). We adjusted the signal to interference range that only direct neighbours successfully receive each other's packets (received signal power: $P_{rec} \geq 0.3$). We varied the interference range from 0% to 100% of the network nodes. The simulation compares throughput of multiple state of the art routing protocols with MR. We simulated Constraint Flooding, Adaptive Tree, Real Time Search and Spanning Tree which are selected as they are basic underlying routing methods for many popular ad-hoc routing protocols. TABLE I shows the parameters and Fig. 5. presents results.

TABLE I. SIMULATION PARAMETER

Parameter	Value	Explanation
Power distribution	$P_{rec,ideal} = P_{trans} \cdot f(x)$	$f(x) = \frac{1}{1+x^2}$
Fading effect	$P_{recl} = P_{trec,ideal} \cdot (1+\alpha(x)) \cdot (1+\beta(t))$	$\alpha = \beta = 0$

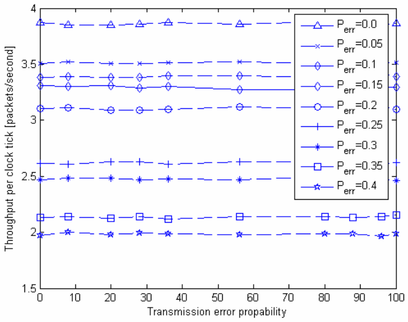

Fig. 4. Throughput in Matrix Routing as a function of packet loss due to interference and different transmission error probabilities.

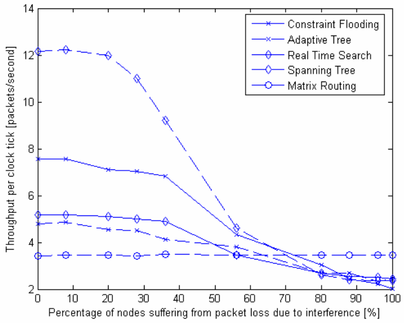

Fig. 5. Throughput as a function of packet loss due to interference

The initialization process quadratically depends on the number of nodes. Moreover the throughput in MR does not depend on the given topology. We investigated the impact of various channel models and transmission error probabilities (Fig. 4.). Increasing transmission error probability causes the throughput to decreases. But increasing interference range does not affect throughput of MR. The throughput in interference scenarios affects the other routing algorithms considerably, while keeping almost constant in MR. As expected, due to the static nature and the TDMA like, simple algorithm, MR is outperformed by all state of the art routing algorithms in low and medium interference range scenarios. When interference range reaches more than 60-70% of nodes, throughput of MR outperforms all other algorithms. Thus MR is well suited for sensor networks with interference affecting at least 60% of the networks sensor nodes.

6. Discussion

Matrix Routing is well suited for the use in real-time applications, where maximum delivery time can be guaranteed by the *routing* algorithm. In contrast to any other approach, MR can give such guarantees due to its static assignment behaviour. It is a low cost, low traffic and easy to implement algorithm, suited for sensor nodes with extremely minimal computational power and memory available without Interference Graphs, flooding based negotiation processes or node clustering and only a minimum overhead compared to other algorithms. Due to its TDMA nature the nodes exactly know when to wake up beforehand. This allows to switch of energy consuming RF units for the remaining time. This way the protocol allows *zero overhearing* costs and *minimal idle listening*. We proposed an initial algorithm for challenging RF scenarios where high interference ranges prevent state of the art routing protocols from achieving a justifiable throughput. The current protocol is actually verified in a real-world implementation with various settings based on Particle Computers cPart (8051 CPU, 64kB Flash, 2 kB RAM 19.2kBit/s data rate) installed in our University building, with encouraging preliminary results basically showing the same behaviour as in our simulation.

The current MR protocol has two major limitations: Low overall throughput due to static assignment of nodes and slow (re)construction of the network topology. Both limitations are caused by the rather static assignment of nodes within the network matrix. Low overall assignment is caused by the fact that the matrix increases quadratically with the number of nodes slowing down the initialization phase. While the sending process is well optimized, initialization and reorganization need multiple cycles to determine sending slots. In areas with a high transmission to interference range factor MR creates lower throughput than other approaches. Matrix Routing's use is also limited in highly mobile settings. If the sensor network changes due to mobile nodes the affecting nodes need to be reintegrated in the network which – under certain conditions – affects other nodes in the network.

7. Conclusion and Outlook

We proposed a new self organizing routing protocol, Matrix Routing, which is specially suited for worst case interference range scenarios. MR is insensitive to interference ranges on the RF channel, shows low complexity and low resource consumption for the sensor node and creates minimal network traffic overhead. MR is very suitable for high dense sensor network settings, with low mobility but high RF interference between nodes, and for settings where an upper time limit for transmission time is required from a routing protocol (e.g. real-time settings). We are currently extending our approach towards more efficient use of sending slots, and towards maximising resilience and reliability in settings with high transmission and high interference errors.

8. References

[1] D. D. Falconer, F. Adachi and B. Gudmondson, "Time Division Multiple Access Methods for Wireless Personal Communications", IEEE Communications Magazine, January

[2] J. Li, C. Blake, D.S.J. De Couto, H. I. Lee and R. Morris, "Capacity of Ad Hoc Wireless Networks", Proc. of the 7th ACM Int. Conf. on Mobile Computing and Networking, Rome,

[3] T. Nandagopal, T.-E. Kim, X. Gao and V. Bharghavan, "Achieving MAC Layer Fairness in Wireless Packet Networks", In Proceedings of ACM/IEEE MobiCom, 2000

[4] W. Lin, C. Zhang, M. Li and M.-Y. Wu, "An Interference Graph Based MAC Protocol for Ad Hoc Wireless Networks", The 6th IEEE Int. Conf. on Comp. and Inf. Technology, CIT

[5] K. Xu, M. Gerla and S. Bae, "Effectiveness of RTS/CTS handshake in IEEE 802.11 based ad hoc networks", Journal of Ad Hoc Networks,

[6] N. Narasimha Datta and K. Gopinath, "A survey of routing algorithms for wireless sensor networks", Journal of the Indian Institute of Science,

[7] J. N. Al-Karaki and A. E. Kamal, "Routing Techniques in Wireless Sensor Networks: A Survey", IEEE Wireless Communications, 12/2004

[8] W. Heinzelmann, J. Kulik and H. Balakrishnan, "Adaptive Protocols for Information Dissemination in Wireless Sensor Networks", Proc. 5th ACM/IEEE Mobicom, Seattle, 1999

[9] J. Kulik, W. Heinzelmann and H Balakrishnan, "Negotiate-Based Protocols for Dissemination Information in Wireless Sensor Networks", Wireless Networks, vol. 8, 2002, pp- 169-85

[10] C. Intanaginwiwat, R. Govondan and D. Estrin, "Directed Diffusion: a Scalable and Robust Communication Paradigm for Sensor Networks", Proc. ACM MobiCom 2000, Boston

[11] F. Ye et al., "A Scalable Solution to Minimum Cost Forwaring in Large Sensor Networks", Proc. 10th Int. Conf. Comp. Commun. And Networks, 2001, pp. 304-09

[12] Y. Yao and J. Gehrke, "The Cougar Approach to Internet Query Processing in Sensor Networks", SIGMOD Record, Sept. 2002

[13] N. Sadagopan et al., "The ACQUIRE Mechanism for Efficient Querying in Sensor Networks", Proc. 1st International Wksp. Sensor Network Protocol and Apps. Anchorage, AK, May 2003

[14] G. Simon, P. Völgyesi, M. Maróti and Á. Lédeczi "Simulation-based optimization of communication protocols for large-scale wireless sensor networks", IEEE Aerospace Conference, 2003

[15] S. Khurana, A. Kahol and A.P. Jayasumana, "Effect of hidden terminals on the performance of IEEE 802.11 MAC protocol", Proc. of the 23rd Ann. Conf. on Local Comp. Netw., 1998,

[16] D. Ganesan, B. Krishnamachari, A. Woo, D. Culler, D. Estrin and S. Wicker. "Complex Behaviour at Scale: An Experiment Study of Low-Power Wireless Sensor Networks", Technical Report UCLA/CSD-TR 02-0013

[17] H. Karl and A. Willig, "Protocols and Architectures for Wireless Sensor Networks", ISBN-13 978-0-470-09510-2 (HB)

[18] S. Kim, S. H. Son, J. Stankovic, and Y. Choi, " Data Dissemination over Wireless Sensor Networks," IEEE Comm. Letters, vol. 8, no. 9, 2004.

[19] T. He, J.A. Stankovic, C. Lu and T. Abdelzaher, "SPEED – A Real-Time Routing Protocol for Sensor Networks"

[20] Y. Zhang and M. Fromherz, "Constrained Flooding: A Robust and Efficient Routing Framework for Wireless Sensor Networks"

[21] D. England B. Veeravalli and J.B. Weissman, "A Robust Spanning Tree Topology for Data Collection and Dissemination in Distributed Environments", IEEE Trans. on parallel and distr. systems, vol. 18, 2007

[22] Y. Zhang and Q. Huang, "Adaptive tree: a learning-based meta-routing strategy for sensor networks". 3rd IEEE CCNC 2006

[23] 802.15.4-2006, IEEE Standard for Information technology-Telecommunications and information exchange between systems,:2006