Towards Energy Efficient, High-Speed Communication in WSNs

Attila Nagy and Olaf Landsiedel

[1] Gothenburg University, Sweden
[2] Chalmers University of Technology, Sweden
{nagat@student.chalmers.se,olafl@chalmers.se}

Abstract. Traditionally, protocols in wireless sensor networks focus on low-power operation with low data-rates. In addition, a small set of protocols provides high throughput communication. With sensor networks developing into general propose networks, we argue that protocols need to provide both: low data-rates at high energy-efficiency and, additionally, a high throughput mode. This is essential, for example, to quickly collect large amounts of raw-data from a sensor.

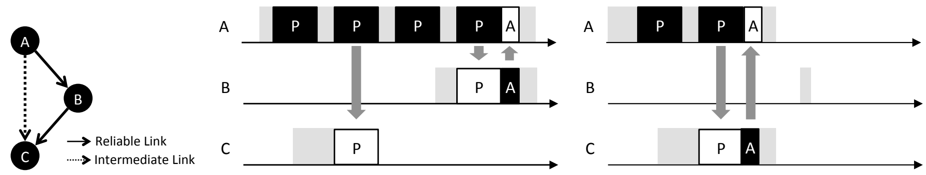
This paper presents a set of practical extensions to the low-power, low-delay routing protocol ORW. We introduce the capability to handle multiple, concurrent bulk-transfers in dynamic application scenarios. Overall, our extensions allow ORW to reach an almost 500% increase in the throughput with less than a 25% increase of the power consumption during a bulk transfer. Thus, we show that instead of developing a new protocol from scratch, we can carefully enhance an existing, energy-efficient protocol with high-throughput extensions. Both the energy-efficient low data-rate mode and the high throughput extensions transparently coexist inside a single protocol.

Keywords: high-throughput, opportunistic routing, Wireless Sensor Network

1 Introduction

In *wireless sensor networks (WSNs)*, most protocol stacks are designed for low data-rates. This is a widespread application scenario in WSNs and matches the limited resources of sensor nodes in terms of bandwidth and energy. However, there is a set of situations, in which we demand for high-speed bulk-transfers: the energy efficient transport of large amounts of data through the resource constrained WSNs. Such scenarios, for example, include the distribution of OS updates and configurations, or the collection of raw measurement traces and logs from individual nodes.

In this paper we argue that instead of developing a new protocol, it is sufficient to extend an existing energy-efficient, low data-rate protocol with a set of carefully designed high-throughput extensions. For this, we base our design on the existing energy-efficient, opportunistic routing protocol, *ORW* [6]. Our



(a) Sample topology: Node A reaches C via B on reliable links or directly on an unreliable link.

(b) Traditional unicast routing in WSNs: Although C might overhear some transmission from A, packets are addressed to B to ensure stable routing.

(c) Opportunistic Routing in ORW: The first node that wakes up, receives a packet, and provides sufficient routing progress acknowledges and forwards it.

Fig. 1. Basic idea of ORW: Utilizing the first woken neighbor as forwarder, ORW reduces energy consumption and delay. This exploiting of spatial and temporal link diversity also increase resilience to link dynamics.

extensions cover a wide range of scenarios including intra-path interference, inter-path interference and concurrent bulk transfers. We provide three key mechanisms:

1. Our first extension to the ORW protocol initiates a novel collision avoidance method for high-throughput scenarios. It is applied beside the already existing, well functioning collision detection technique for low data-rate settings.
2. The second extension's purpose is to stabilize the EDC routing metric used by the ORW protocol to estimate the latency, i.e., duty-cycled wake-ups, required for a packet to reach the sink from a given node.
3. The third extension disables duty-cycling during a bulk transfer for the nodes that are participating in an ongoing bulk transfer.

The remainder of this paper continues by briefly discussing the ORW protocol to provide the required background in Section 2. We describe related work in Section 3, and show the design of our high-throughput extensions to the ORW protocol in Section 4. Section 5 evaluates these extensions and we conclude in Section 6.

2 Background

ORW targets duty-cycled protocol stacks. For simplicity we here illustrate the basic concept of ORW utilizing an asynchronous low-power-listening MAC, such as in X-MAC [1]. In low-power-listening a sender transmits a stream of packets until the intended receiver wakes up and acknowledges it (see Fig. 1b). To integrate opportunistic routing into duty cycled environments, we depart from this traditional unicast forwarding scheme in one key aspect: The first node that (a) wakes up, (b) receives the packet, and (c) provides routing progress, acknowledges and forwards the packet, see Fig. 1c. For example, in Figure 1a node A

can reach node C either directly via an unreliable link or via B. Commonly, traditional routing ignores the unreliable link $A \rightarrow C$ and relies on $A \rightarrow B \rightarrow C$ for forwarding. ORW extends this, by also including $A \rightarrow C$ into the routing process: If $A \rightarrow C$ is temporary available and C wakes up before B, ORW will utilize it for forwarding. This reduces the energy consumption and delay (see Fig. 1c). To select forwarders, ORW introduces EDC (Expected Duty Cycled wakeups) as routing metric. EDC is an adaptation of ETX [2] to energy-efficient, anycast routing in duty-cycled WSNs.

Our design enables an efficient adaptation of opportunistic routing to the specific demands of wireless sensor networks: (1) In contrast to opportunistic routing in mesh networks, forwarder selection in ORW focuses on energy efficiency and delay instead of network throughput: It minimizes the number of probes until a packet is received by a potential forwarder. (2) It integrates well into duty-cycled environments and ensures that many potential forwarders can overhear a packet in a single wake-up period. Thereby, ORW exploits spatial and temporal link-diversity to improve resilience to wireless link dynamics. (3) The fact that only a small number of nodes receive a probe at a specific point in time simplifies the design of a coordination scheme to select a single forwarder. This limits overhead of control traffic.

However, in the design of ORW we focused on low data-rate traffic, as this is the most common scenario in WSNs. In this paper, we now take the next step and widen our application scenarios: We extend ORW to high-throughput settings, i.e., to support bulk transfers.

3 Related Work

There exist several approaches to high-throughput communication in WSNs. For instance, *Packet in Pipe* [7] (PIP) is a connection-oriented, multi-hop, multichannel, TDMA-based solution. Another approach is *Flush* [5], a CSMA-based protocol applying a rate-control algorithm along with end-to-end acknowledgments. Both of these protocols are not designed to handle multiple concurrent bulk transfers. Moreover, they do not integrate well with other routing protocols. Their design is tailored to being the only routing protocol in place at a specific point in time. We argue that this assumption is not practical as low data-rate applications are the common application scenario in WSN. Thus, we believe any high-throughput protocol must co-exist efficiently with low-data rate protocols.

On the other hand, the *Lossy Link, Low Power, High Throughput* [4] protocol (LLH) allows for several concurrent bulk transfers crossing each others paths. This protocol uses duty-cycling with low-power listening, has a high resistance against both intra-path and inter-path interference, and applies a CSMA based MAC protocol. From these three high-throughput solutions the LLH resembles the most to the extended ORW protocol due to its low-power property and the capability to handle concurrent bulk transfers. However, in contrast to our work, LLH assembles a new protocol to be deployed alongside with existing low-power, low-rate protocols. This leads to an increased code base and potentially

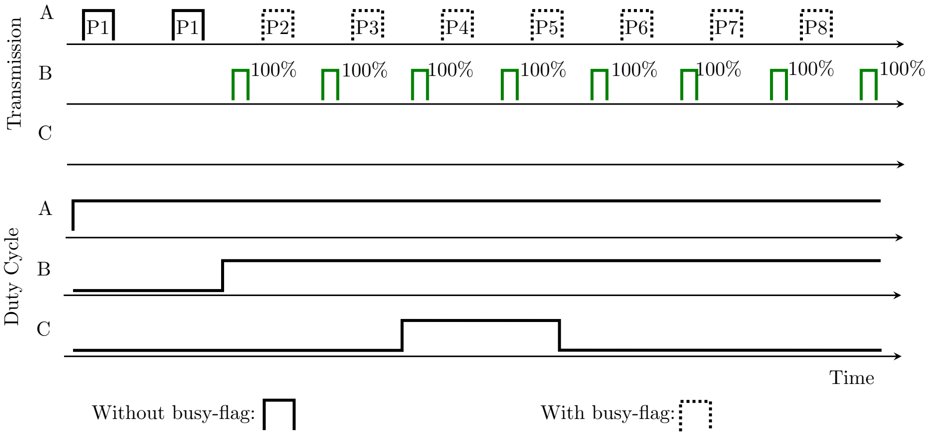


Fig. 2. Collision avoidance by the extensions: Node B forwards all the packets from node A. When node C starts its duty cycle, it receives the packets with busy-flag, and therefore does not acknowledge them.

additional energy consumption, as two protocols need to be operated in parallel. As a result, the may both have own state and each map apply own network maintenance such neighbor discovery or wireless link estimation.

4 Design

In this section, we identify the limitations of ORW in high-throughput scenarios and next introduce three extensions to enable high-throughput communication in ORW.

4.1 Limitations of ORW in High-Throughput Scenarios

We begin with a discussion of the limitations of ORW in presence of high datarates. The base ORW protocol performs poorly in the bulk transfer scenario due to the following key problems: (1) contention and packet collisions, (2) unstable routing metrics, and (3) early termination of duty cycles.

1. **Problem: High Contention and Packet Collisions.** Bulk transfers are streams of packets leading to many, concurrent transmissions in the network. This inherently increases contention and as a result the possibility of collisions, especially when there are multiple possible paths for a packet between the source node and the sink node.
2. **Problem: Unstable EDC Routing Metric.** EDC as routing metric in ORW estimates the expected duty cycles that are required for a packet to traverse the topology from a node to the sink. Our analysis indicates that this metrics tends to fluctuate rapidly in case of high contention. This is especially the case in topologies where the path of a bulk packet has a high number of hops but just a few possible paths exist for the packet. The result

of this fluctuation are loops in the packet's path and, via these loops, packet loss.

3. **Problem: Nodes do not stay awake until burst is completed.** Duty-cycling during a bulk transfer can lead to situations where nodes that are heavily used turn off their radio receiver, as their duty cycles have expired. This forces ORW to find a new, alternative forwarder or to wait for that particular forwarder to wake-up again. As a result, it increases the transmission time of packets and the power consumption of the whole network.

4.2 Extending ORW to High-Throughput Scenarios

In the following, we present our extensions to ORW to mitigate the challenges discussed above and to enable energy-efficient and reliable high-throughput communication.

Collision Avoidance: Our collision avoidance extension is divided into two parts: a sender and a receiver part. In the sender part, the design contains a special flag, the *busy-flag*. A sender sets it to indicate that it has locked onto a specific forwarder to transfer a bulk of packets. A forwarder shall only forward packets from senders that have locked onto it. Other potential forwarders shall, upon receiving packets with the the flag set, not forward it and quickly go back to sleep to safe energy. As a result, this extensions limits contentions between nodes to be elected as forwarder. Figure 2 illustrates how this collision avoidance extension works with one sender node A and two receiver nodes B and C.

Stabilizing the EDC routing metric: ORW, by default, updates its routing estimates after each transmission. Thus, based on its success or failure the quality estimation of the wireless link to the neighboring nodes is updated. In high-throughput scenarios, with many current transmissions this leads to erroneous estimates. Our solution is to simply prohibit the EDC update of a node if it is involved in a bulk transfer. Thus, we update the routing metric at the end of each bulk transfer, i.e., after 10 to 20 packets, and not during it.

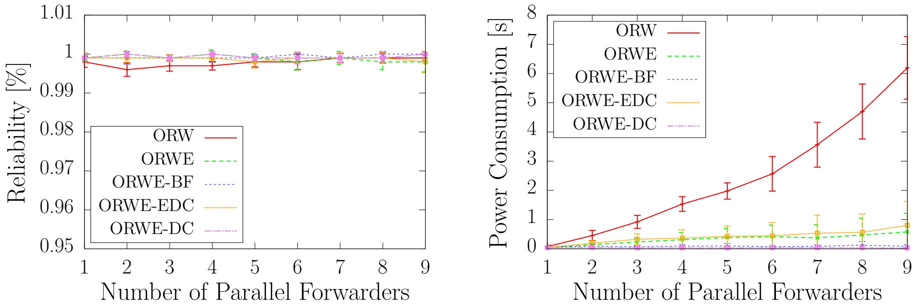
Keeping nodes awake: Finally, we prohibit nodes that are involved in a bulk transfer from going back to sleep before the bulk transfer has completed.

5 Evaluation

Our evaluation presents two types of benchmarks: (1) micro-benchmarks and (2) macro-benchmarks. For the micro-benchmarks we use a WSN simulation environment, Cooja, and for the macro-benchmark we utilize Indriya [3], a three-dimensional wireless sensor network deployed across three floors of the National University of Singapore.

The micro-benchmarks use two types of metrics: (1) reliability, (2) power consumption of the whole bulk transfer. We evaluate each of our three extensions separately and we show their combination:

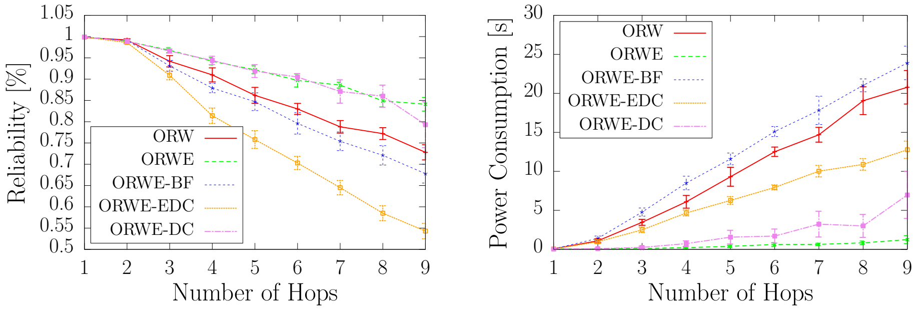
1. ORWE-BF: busy-flag extension to avoid contention and collisions.
2. ORWE-EDC: stabilization of the EDC routing metric.



(a) **Reliability:** Our extensions have the same level of reliability as the base ORW design.

(b) **Power consumption:** Drastic increase in the ORW design when the topology increases. In contrast, our extensions show only a minimal increase.

Fig. 3. Parallel forwarder nodes.



(a) **Reliability:** ORWE has a higher reliability than the base ORW protocol.

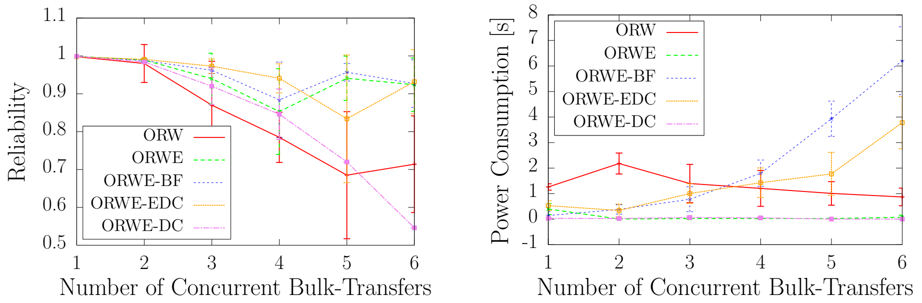
(b) **Power consumption:** ORWE has the lowest power consumption.

Fig. 4. Intra-path interference.

3. ORWE-DC: stabilization of the duty-cycle.
4. ORWE: the combination of all three extensions.

Our micro-benchmarks evaluate three types of scenarios in a controlled environment. The first scenario, inter-path interference, shows the best performance improvement. The topology we use for this type contains a set of parallel forwarder nodes between the source and sink nodes. The more potential forwarders we deploy, the higher the chance for collisions of acknowledgments is. While the base ORW protocol resolves collisions per packet, our extensions allow to lower this intensity to one collision per bulk transfer. Figure 3 shows the reliability and power consumption of this scenario: The power consumption stays on a low level without any performance degradation in the reliability.

The second type of scenario, intra-path interference, aims to show the performance of our extensions in a topology where there is only one path between



(a) **Reliability:** The bottleneck scenario highlights the limitations of all design: the contention leads to packet losses in all designs. Nonetheless, ORWE improves over default ORW.

(b) **Power consumption:** ORWE has the lowest power consumption.

Fig. 5. Bottleneck scenario: Multiple sources with 4 potential forwarders.

the source and the sink, but that path contains a high number of hops. In this scenario, the extensions perform significantly better than the base protocol in all the metrics. For instance, ORWE uses the 10% of the power that is used by the base ORW protocol for the same bulk transfer. Moreover, we increase the reliability in the meantime. Figure 4 shows the reliability and power consumption for this scenario. The third type of scenario shows that our extensions are capable of handling multiple concurrent bulk transfers with only a minor performance degradation.

The third type of topology evaluates a case when a number of source nodes concurrently sending bulk packets exceeds the number of forwarders, see Figure 5. This topology formulates a bottleneck scenario in the sense that the number of forwarder nodes are not able to serve the performance demand generated by the source nodes creating a special collision critical situation.

The macro-benchmark serves as a platform for the evaluation on a larger scale. Overall, our results show that our extensions use 25% of the power that are used by the base ORW protocol with a slightly higher reliability.

6 Conclusion

In this paper we show, that by adding three carefully designed extensions to the ORW protocols, we can extend it from a low data-rate protocol to also support high-throughput scenarios at high energy-efficiency. Our future work includes a detailed testbed evaluation and an experimental comparison to the state of the art.

Conversely, by applying our extensions we obtain a significant performance improvement in all the metrics that we presented in this paper. Lastly, these extensions have no effect on the non-bulk packet transfer, since they are only activated when the transmission rate exceeds a certain level. Thus, these extensions transparently integrate into ORW and are backwards compatible with the base protocol.

References

1. Buettner, M., Yee, G.V., Anderson, E., Han, R.: X-MAC: a Short Preamble MAC Protocol for Duty-Cycled Wireless Sensor Networks. In: SenSys: Proc. of the ACM Int. Conference on Embedded Networked Sensor Systems (2006)
2. De Couto, D.S.J., Aguayo, D., Bicket, J., Morris, R.: A High-Throughput Path Metric for Multi-Hop Wireless Routing. In: MobiCom: Proc. of the ACM Int. Conference on Mobile Computing and Networking (2003)
3. Doddavenkatappa, M., Chan, M.C., Ananda, A.L.: Indriya: A low-cost, 3d wireless sensor network testbed. In: TRIDENTCOM. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, Springer (2011)
4. Duquennoy, S., Österlind, F., Dunkels, A.: Lossy links, low power, high throughput. In: Proceedings of the 9th ACM Conference on Embedded Networked Sensor Systems. SenSys '11 (2011)
5. Kim, S., Fonseca, R., Dutta, P., Tavakoli, A., Culler, D., Levis, P., Shenker, S., Stoica, I.: Flush: A reliable bulk transport protocol for multihop wireless networks. In: Proceedings of the 5th International Conference on Embedded Networked Sensor Systems. SenSys '07 (2007)
6. Landsiedel, O., Ghadimi, E., Duquennoy, S., Johansson, M.: Low power, low delay: Opportunistic routing meets duty cycling. In: IPSN'12: Proceedings of the 11th ACM/IEEE International Conference on Information Processing in Sensor Networks (April 2012)
7. Raman, B., Chebrolu, K., Bijwe, S., Gabale, V.: Pip: A connection-oriented, multi-hop, multi-channel tdma-based mac for high throughput bulk transfer. In: Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems. SenSys '10 (2010)