Interference Aware Routing and Load Balancing in Wireless Sensor and Actuator Networks

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Abstract. In wireless sensor and actuator network (WSANs) there usually exists critical data, such as alarms and emergent event reports, that require short time delivery with high reliability but data volume is relatively small. At the same time, there exists larger volume of bulk sensor data which typically is delay tolerant and should be transmitted in the most energy efficient manner. On the 2.4 GHz ISM-band, the coexistence of the WSANs with WLANs imposes great challenge for designing reliable WSAN protocols. In this paper, we propose new sink initiated routing protocol that supports the two above mentioned traffic classes and is aware of the interference situation of the network. Critical data is transmitted using most interference resilient and reliable paths that minimize the expected transmission delay while the bulk data is transmitted in the most energy efficient manner by applying load balancing over several paths. The use of load balancing aims to even out the energy consumption of the intermediate nodes and thus maximize the operation time of the network. Our routing protocol estimates the link reliability based on the strength and activity of the interference as well as the path loss of the link and is able to adapt the routes based on changes in the propagation conditions and WLAN interference.

Key words: WSANs, Interference Aware Routing, Load Balancing, Multipath routing

1 Introduction

Wireless Sensors and Actuator Networks (WSANs) enable designing of novel and intriguing applications that can be used to address numerous industrial, environmental, societal and economical challenges. In WSANs, low-power sensors collect information about the physical world which is then transmitted wirelessly to actuators. Based on this reported information, actuators perform desired actions. Often in WSANs, there is no need for real-time communication, however, in real-time process control it is essential that the measurements and other critical data are delivered with minimum delay and maximum reliability. Recent years has seen growing industrial interest towards using WSANs for real-time applications, such as process control. Traditional control theory is based on the

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assumption of deterministic measurements with fixed delays. There are several approved and reliable solutions exist for wired communications. However, these solutions are not feasible for WSANs due to the random delays introduced by the underlying wireless medium access protocols.

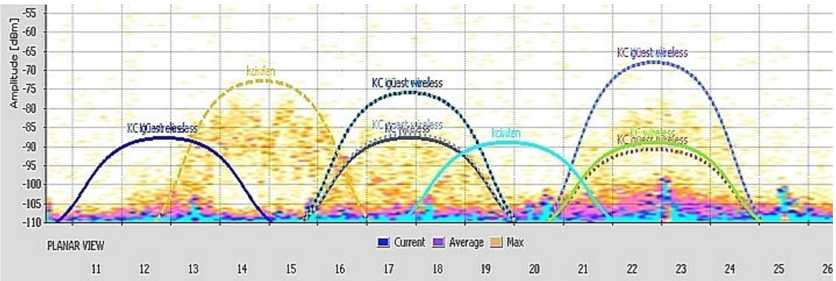

Fig. 1. Demonstration of spectrum measurement results in an industrial warehouse. The numbers on the x-axis denote IEEE 802.15.4 channels and measured power levels are represented on the y-axis.

Another challenging issue is the coexistence of high power wideband wireless local area networks (WLAN) and low power wireless sensor and actuator networks (see Fig. 1). In case of IEEE 802.11b and g transmitters, one can find three IEEE 802.15.4 channels that are orthogonal to the WLAN channels. That is, they only experience adjacent channel interference which is at least 30 dB lower than the interference on the signal band. For IEEE 802.11n, the situation gets worse and there is only single IEEE 802.15.4 channel that only experience adjacent channel interference. The general conclusion is that coexistence on the same band is possible if there is enough spatial separation between the systems. Increasing transmission power could be an exciting approach against WLAN interference; however this introduces self interference within 802.15.4 networks. Also it is not trivial to make an optimal power control scheme, since the actual transmission power does not scale linearly with the power settings available on the devices. Another alternative is to use multipath routing, i.e. if there is enough spatial separation between relay nodes, then each next-hop node would experience different channel interference. Hence, multipath routing to some extent inherits resilience against WLAN interference.

Also, a common feature among WSANs applications is that the data will be gathered to a sink for the decision making process and hence, it is feasible to assume that a GW node exists in all WSAN applications. Some examples applications are Greenhouses, Condition Monitoring, Crane Control System and Energy Production System. Therefore, communication protocols should take into account these special properties of WSANs, such as delay-constrained, reliability and network topology, i.e. convergence of data towards the GW.

In this paper, we introduce a real time networking protocol called Sink Initiated Routing Protocol (SIRP). SIRP is designed especially for time-constrained wireless sensor and actuator networks (WSANs). SIRP combines interference aware routing and load-balancing techniques, to achieve robustness and improve energy efficiency of the network. Also our protocol enables global time synchronization by utilizing periodic initialization packets. Since distances between neighboring nodes are generally small in WSANs, one way time synchronization can be exploited, such as [1]. This way time synchronization hierarchy and network topology will be updated every round and thus, the impact of node failures will last only until the end of that particular round. The performance of SIRP will be compared to other existing solutions and using simulations we show that SIRP outperforms alternative designs. The rest of the paper is organized as follows. In Section II we briefly review related work and the proposed SIRP will be introduced in Section III. Simulation results are presented in Section IV. Finally, Section V concludes the paper.

2 Related Work

Due to convergent nature of data flow in many WSANs applications, the communication is predominantly from sensors to sink nodes. Standard routing solutions for other types of networks (e.g. ZigBee, MANET) cannot be employed directly to WSANs, ZigBee which is based on Adhoc On-demand Distance Vector Routing (AODV) routing protocol [5] is mainly intended to discover a single route between a source and destination node. AODV is not an optimal solution for WSANs, since it introduces higher power consumption and requires significant routing overhead to accomplish many to one communication.

Heterogeneous nature of WSANs is a good reason to employ hierarchical routing, thus, more complicated data processing operations can be transferred to cluster heads. Due to data aggregation and fusion in the cluster heads, the number of transmitted messages in the WSAN can be significantly reduced, and, consequently, the energy efficiency increased. As a representative of hierarchical routing methods in WSANs, we consider the Ripple-Zone (RZ) routing scheme [2], the introduced hierarchical routing algorithm uses the concept of a Ripple-Zone (RZ) around each actuator. Sensors are assigned to different ripples based on their distances in number of hops from the actuator. In each ripple, some sensors are chosen to perform as masters based on the Topology Discovery Algorithm (TDA) previously proposed by the authors. Each master collects data from the sensors in its zone and then transmits data to a master in the next ripple that is closer to the actuator. The Ripple-Zone (RZ) routing scheme was compared with LEACH [3], ZRP [4] and flat-topology based schemes in terms of energy efficiency. The authors have proven that their protocol is energy efficient, reliable and scalable, moreover, it can adapt to changing network topology by employing the local link failure repair method. However, it would be interesting to know, how the scheme performs in terms of latency, since it is a crucial point in most of the WSAN applications.

Similarly, the tree-based algorithm has a few shortcomings 1)Existence of bottleneck, especially nodes closer to the sink 2)They are more susceptible to node failure. SIRP is a multipath routing protocol; hence we implement load-balancing algorithm which minimizing these bottle necks. There have been developed a number of multipath routing protocols, Adhoc On-demand Multipath Distance Vector Routing (AOMDV) [6] that is an extension to the AODV protocol for computing multiple loop-free and link-disjoint paths. In our simulation results we show that AOMDV is expensive with respect to bandwidth and power consumption.

Therefore, the solution presented in this paper addresses the requirements of a real-time control system and takes into consideration the challenges of the industrial environment in the system design. Even though the solution addresses different aspects of the complex problem, it still remains simple and easy to implement on top of IEEE 802.15.4 compliant platforms.

3 Protocol Description

In wireless sensor and actuator network there usually exists critical data that require short time delivery but data volume is relatively low (such as fire alarm, emergent event report). These data must be treated separately since they are time constrained. Therefore routing protocol should establish interference resilient links to support such communication requirements. Hence our protocol support two types of routes minimum delay Routes and a backup interference resilient route in case of critical data. SIRP achieves the following features:

1. Actuator/sensor communication and actuator/sensor communication.
2. Establishes multiple minimum delay routes for transfer of critical data.
3. Dynamic interference aware routing algorithm for successful operation in challenging environment.
4. Protocol simplicity.
5. Scalability
6. Increased network life using load balancing.

3.1 Routing Metric

In this section, we present the routing criteria to establish minimum delay routes. In SIRP, each node estimates the channel access time (CAT), waiting time of a given packet before transmission begins. CAT is a measure of the MAC layer congestion in the local neighborhood of the node and it is counted for each transmission attempt separately. That is, it does not consider retransmission delays due to unreliable transmission - link reliability is already considered in the interference part of the routing metric. In actual implementation, this task could be done by implementing a timer function, which computes the average delay of a packet before the transmission occurs. More details on route establishment will be covered in sub-section 3.4.

An estimated delay of each *(i,j)* link can be found by Little's Law.

$$\hat{T} = \frac{\hat{N}}{\hat{\lambda}} \tag{1}$$

where $\hat{\lambda}$ is given by Eq. 2 and $\hat{N}$ the expected number of packets in queue,

$$\hat{\lambda}(t+1) = (1-\alpha)\hat{\lambda}(t) + \alpha x(t), \tag{2}$$

with $\alpha \in (0,1), x(t) = \begin{cases} 0, & \text{no arrival} \\ 1, & \text{arrival} \end{cases}$

3.2 Estimating Strength and Activity of the Interferer

Fig. 2 clearly illustrates that 'activity' and 'strength' of the WLAN interferer has significant effect on the packet delivery of 802.15.4 nodes. Our goal is to offer interference resilience routes in case of critical data transmission. We assume that using existing energy detection capabilities of 802.15.4 nodes, it is possible to determine the *strength* of a WLAN interfere. This assumption is reasonable since there already exists various methodology to reliably estimate interference level, see [11]-[12]. During network initialization, each node will distributes this information to all its neighbors. Nodes are then able to evaluate the corresponding link *SINR*.

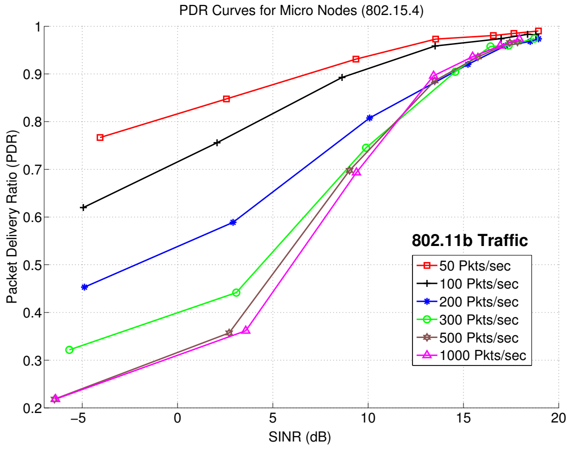

Fig. 2. Experimental packet delivery curves for micro nodes (802.15.4 compatible) under co-existence with 802.11b WLAN interferer.

Periodic channel sensing is done to estimate the activity of the interferer using the following equation $\frac{\tau^i_{busy}}{T}$, where τ^i_{busy} is the time fraction that channel is sensed busy for node i, and T is the normalized overall sensing time. Based on the recently estimated activity and strength of the interferer, a transmitting node computes the drop probability of the link from the Fig. 2.

3.3 Load Balancing for Bulk Data

Multipath routing is a good means to provide resilience by transmitting multiple packet copies over multiple paths, and to distribute energy utilization among nodes by load balancing. An advantageous feature of WSANs that encourages employing multipath routing is high node density due to which there exist many paths with dissimilar link quality as that of the primary path. Load balancing scheme for WSANs is considered in SIRP. The main idea is to reduce utilization of network resources by splitting the data packet into k packets and sending these packets on multiple paths. The number of packets sent on each nexthop node depends on the corresponding link *SINR*, recent activity of the channel and residual battery energy of the prospective node.

3.4 Sink Initiated Routing Protocol

This section present in detail our proposed routing scheme, which integrates all functionalities describe in sub-section 3.13.2 & 3.3.

1. In SIRP actuator or gateway initiates the routing procedure by sending a broadcast messages. The proposed algorithm runs locally on each node and moves on as a *wave* from the GW. The broadcast message for $node_i$ consists of the following fields.
   - Hop count: Number of hops to the gateway.
   - Interference Level (dB) at $node_i$: We assume that using energy detection capabilities, devices are able to estimate the strength of the WLAN interferer. Channel is scanned periodically and the interference level is updated.
   - T is the accumulated delay information carried by the incoming broadcast message. τ_i is the expected delay at $node_i$. Therefore, the total accumulated delay from $node_i$ to the gateway is computed as $(T + \tau_i)$.
   - Energy left in the battery of $node_i$
   - Sequence number of the broadcast wave, on every new broadcast the gateway increments the sequence number. This serves as an indication to all receiving nodes that route entries corresponding to older sequence number should be purged.
   - Packet Time stamping is done to achieve global time synchronization, which is essential for innumerable WSAN applications, for example industrial automation [7].
2. Up on receiving broadcast message, each relay node should add the new route entry only:
   - if the accumulated delay time is less than the maximum tolerable delay defined by the application,
   - if the accumulated delay is greater than the node will simply drop the broadcast message, since the delay requirement does not satisfy the required quality of service.

Further, each nodes should now be able to compute the corresponding *SINR* of the link, this information is stored along with other routing information. In our simulations, we have fixed the maximum number of routes entries for a node.

3. Instead of rebroadcasting these packets immediately, a node chooses to defer its transmission for a random period. The defer time is a function of number of hops from the gateway, that is, higher the number longer is the defer time. This approach reduces the number of routing messages re-broadcasted considerably, thus avoiding collision of routing packets and consequently increasing the probability of route establishment. It also allows nodes further in the network to receive multiple broadcasts from all its precedors. For each intermediate node that has received a new broadcast message (that is, the sequence number is greater), we control the route entry procedure to accommodate multiple routes. If an intermediate $node_j$ receives another copy of broadcast message from the different relay node it will check if its accumulated delay of the forward path is larger than its application requirement,
4. Upon completion of defer timer, intermediate nodes will re-broadcast the message with their own interference level, battery residue value and accumulated delay T. This procedure continues until all the nodes have establishes forward path to the sink.
   a) As said earlier each node scans the channel periodically and updates signal level and activity of the interferer. Now if a node has some critical data to forward,
      - A node simply selects the highest *SINR* link and transmit the packet, thus maximizing the reliability of the transmission.
   b) If a node has some bulk data to forward:
      - Depending on the activity of interferer and link SINR, a node computes drop probability for each link in its routing table. It then does load balancing over a reduced set of links, which assures reliability under current interference activity.
5. Reverse path are then established when data packets from the sensors are sent back to the sink. Each intermediate node on receiving data packets makes a route entry to the source of the date packet. That is when the data packet reaches the sink it would have established a reverse path to the source of the packet i.e. sensor.
6. The frequency of routing initialization phase is controlled by the sink node. That is depending on the network performance and dynamics of the channel a sink node could increase or decrease the route initialization period. This approach complies well with the centralized architecture of wireless sensors and actuator networks.
7. In order to provide additional resilience against link failure, overhearing of messages and subsequent route updates are allowed. Finally, if a link failure is detected a route error message is broadcast. Intermediate nodes with active route information to the sink will quickly respond to these messages.

4 Simulation Results

This section presents the performance of the SIRP scheme in wireless sensors and actuators networks. The impact of the WLAN interference is taken into account. SIRP is compared with the conventional AODV, AOMDV routing protocols. The results for load balancing are also presented.

4.1 Simulation Environment

The implementation is done in ns-2 simulator [8]. This simulator is easily available public domain tool and is considered a de facto standard for implementation and verification of wireless networks. Since there is no support for co-simulation of WLAN and WSANs in ns-2, we have developed a trace based WLAN interference model. The interference model is integrated into WSANs simulations to emulate co-existence scenario. In this approach, we initially configure interference traffic and run simulations for 802.11b networks. The output trace file captures all the distances, timing and packet information of the simulation. This information is then used during WSANs simulations. For instance, when a 802.15.4 compatible node sends a packet, we check from the trace file, if any WLAN transmission occurred in that interval, based on the distance between the interferer and the destination node and the pdrcurves, we evaluate if the current packet should be dropped or not. Similarly, channel sensing and interference level are also integrated. One limitation in this approach is that WLAN network is independent of 802.15.4 network. That is 802.15.4 nodes are invisible to WLAN.

4.2 Resilience against Interference

Simulation is carried out with 50 nodes randomly distributed over an area of 1000x1000m2. Nodes are moving according to the random waypoint model. The traffic generation for 802.15.4 nodes is fixed at 8Pkts/sec. First, we present results obtained for the interference case, Fig. 3a & 3b show packet delivery ratio and average end to end delay plotted versus different WLAN traffic conditions. For both low and high interference scenario, SIRP consistently shows a 10 % increase in packet delivery over single path AODV and multi path AOMDV, whereas significant increase is seen at low interference traffic (approx. 25 % on AOMDV and approx. 50 % for AODV). In case of average end-to-end delay SIRP clearly outperforms other protocols maintaining a min delay of 0.2sec. These results show us the effectiveness of using minimum delay routing metric combined with interference avoidance algorithm.

With load-balanced methods, nodes in a network are involved into network activity with an more evenly distributed manner. This gives fairness in term of energy consumption. Fig. 3c & 3d. shows the mean battery residue and standard deviation of AODV and AOMDV and SIRP for different WLAN traffic.

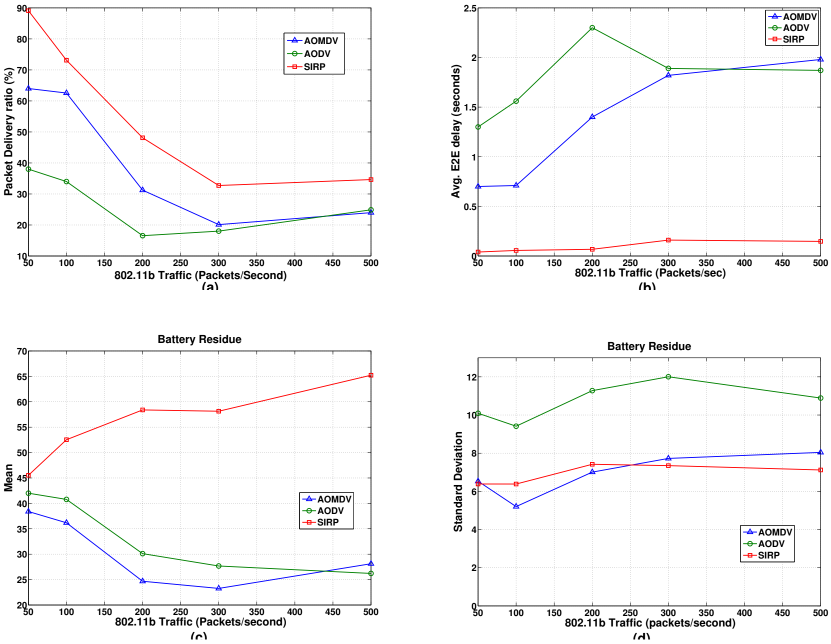

Fig. 3. Simulation Results a) Packet Delivery Ratio b) Average End-to-End Delay c) Mean Battery Residue and d) Standard Deviation

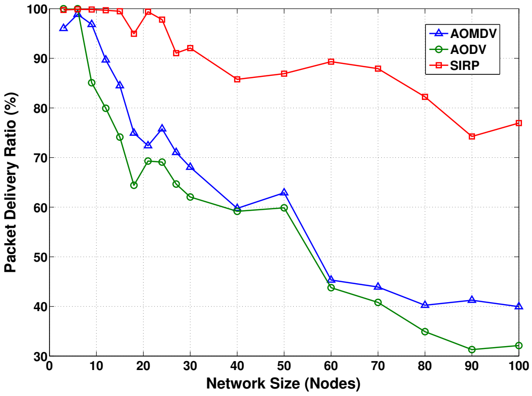

Fig. 4. Scalability for WSANs

4.3 Scalability

In this simulation, nodes are randomly scattered in an area of 50x50m2. We can see from Fig. 4 that SIRP reduces the overall amount of collisions using random defer time, better connectivity is achieved which also improves the overall packet delivery. Unlike AODV & AOMDV, SIRP is a sink initiated routing protocol, which means, the number of route initializations is limited by the number of sinks in the network. This approach is well suited for WSANs as it considerably reduces the overall control overhead. In case of AODV & AOMDV, each source would have to initiate a RREQ mechanism. Hence increasing the overall control messages and subsequently packet collisions.

4.4 Case study: Wireless Air Conditioning System (WACS)

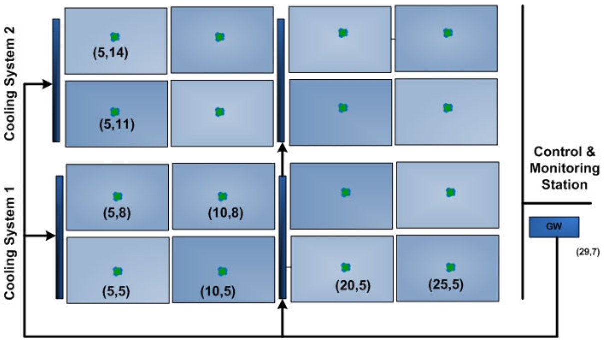

Fig. 5. Wireless Networked Controlled Application

Wireless Air Conditioning System (WACS) maintains the cooling of the industrial hall at the desired temperature (21°C). Here we have a wireless sensor grid network overlaid on the industrial hall; the measurements are taken at a rate of 1/min. The measurements are sent to the central control system access point which is right of the industrial hall. This access point is connected to the wired building automation system that can handle intelligent control tasks and performs cooling operation. The heat sources causing the warming of inside temperature are the lathe machines and the crane control system. Our physical model for ACU considers heat transfer between adjacent areas. We modelled an realistic wireless networked control application in PiccSIM [10]. The objective is to maintain the temperature of an industrial hall at an desired value (21°C). The industrial hall is divided in to 4 segments, each segment represents 4 sensor nodes wirelessly communicating measured temperature value to the command control. Hence depending on the packet delivery of that node the temperature estimate are computed and the subsequent control (heating/cooling) is performed.

The results in Table 1 indicate that SIRP achieves minimum control cost over AODV and AOMDV for ricean k factor equal to 0, which corresponds to maximum drops in the channel. However when the network size is small and minimum drops are seen (for k=20), there would not be any link failures, in such cases, AODV seems to have slightly better cost function than multipath SIRP.

Table 1. Control Cost (integral of squared error (ISE) between desired and actual temperature) of each cells for ricean k factor 0 & 20 respectively

	AODV	AOMDV	SIRP
k=0	13.7059	15.354	12.7822
k=20	10.3857	14.6046	12.459

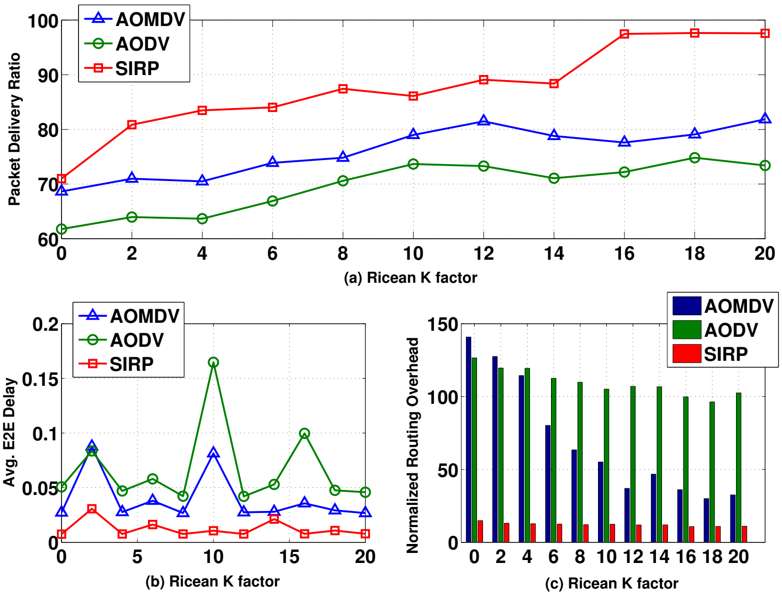

Fig. 6. Packet delivery ratio, Average end to end delay and Routing overhead for AODV, AOMDV and SIRP protocols

The numbers of sensors are significantly higher than the sinks. This means, in case of AODV, AOMDV each sensor initiates a routing mechanism, that is more control overhead for AODV and AOMDV, therefore significantly higher energy consumption. Fig. 6c presents normalized routing overhead for AODV, AOMDV and SIRP. The convergence of all the links to the sink makes SIRP, a practical approach for wireless sensors and actuators networks. SIRP improves reliability (Fig. 6a), minimizes average end to end delay (Fig. 6b) and is an energy efficient routing protocol (Fig. 6c).

5 Conclusions

In this paper we have presented a novel routing protocol, called Sink Initiated Routing Protocol, which is designed particularly for Wireless Sensor and Actuator Networks (WSANs). The proposed protocol achieves higher throughput while offering low packet transmission delays. Scalability is an inherent property due to the localized nature of operation. Frequency of routing initialization phase is adapted to the channel conditions and is used to deliver time synchronization and routing information which further enables rapid recovery from topology changes. The protocol is also robust and performs well under interference which is of significant importance for WSANs operating on unlicensed frequency bands. The protocol has been implemented on ns-2 and we showed a comprehensive set of simulation results, including a real-world industrial application scenario, to confirm that SIRP is suitable for WSANs.

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