SCLD-ATP: Symmetric Coherent Link Degree, Adaptive Transmission Power Control for Wireless Sensor Networks

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Abstract: Wireless Sensor Networks (WSNs) are by nature dynamic and communication between sensors nodes is ad hoc. Numerous protocols and applications proposed operate on the assumption that communication channels are stable. Topology Control Protocols are crucial in the operation of WSNs as they adjust transmission power in order to maintain link quality, minimize interference and provide spatial topological control. Analysis of such protocols is performed using theoretical models that are based on unrealistic assumptions like ideal wireless channels and perfect energy consumption and distance estimations. With these assumptions taken for granted, theoretical models claim various performance milestones that cannot be achieved in realistic conditions. We here present a topology control protocol that is deployable in real WSNs and distance ourselves from spatial, temporal, environmental assumptions regarding the performance of communications on the wireless medium. Our protocol focuses on fault tolerance and symmetric link coherence using an adaptive transmission power scheme. From various testbed experiments we showcase the performance of SCLD-ATP in terms of load balancing, reliability, multi-hop capabilities and power consumption.

1 INTRODUCTION

Wireless Sensor Networks (WSNs) are wireless multi-hop networks comprised of low powered tiny devices with limited processing capabilities and a plethora of sensing attributes (Akyildiz et al., Aug). This emerging and scalable technology has a vast space of different applications like commercial and home building automation, target tracking and health monitoring.

In order to organize these devices into networks that provide adequate quality of service, protocol designers have to deal with two main problems. First comes the problem of maintaining stable and reliable communication between nodes. The reliability and stability of communication in the wireless medium is subject to many factors and temporal qualities. These include external noise, interference from within the network and even hardware misconfigurations and constraints. Due to these problems, communication quality cannot be modeled accurately for all applications (Srinivasan et al., 2010), (Zhao and Govindan, 2003), (Woehrle et al., 2012). We also notice that assisting metrics like LQI and RSSI, cannot describe accurately link qualities in real deployments. Controlled experiments show that equal transmission power settings from multiple senders to one receiver and vice versa, can also produce different link qualities between WSN nodes (Son et al., 2004). Extensive studies show inherent link asymmetry in WSN communications under various settings and hardware configurations (Misra et al., 2012). Secondly, topology control protocols have to create and maintain sufficiently connected, load balanced or even custom attributed neighborhoods of nodes. Spatial control is essential for preserving the multi-hop nature of WSNs and minimizing radio interference and power consumption. Solving these problems is especially hard when WSN system installations are subjected to unpredictable dynamicity like sudden node failures while running applications have to sustain seamless services.

Furthermore, WSN node deployments may be non-uniform, arbitrary, or even mobile with the network topology varying over time. The consequences in these cases are: a) areas where WSN node placement is dense or sparse and communication is redundant or with limited coverage. b) difficulty in determining the network parameters for connectivity, coverage and minimum energy consumption.

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We focused our study towards topology control schemes for WSNs that adjust node transmission powers dynamically. We propose SCLD-ATP (Symmetric Coherent Link Degree, Adaptive Transmission Power), a protocol designed from a perspective of providing a continuous service that monitors and delivers sufficient, reliable communication between WSN nodes efficiently. The key characteristics of our proposed protocol are: *a*) simplicity in terms of communication without any deliberate organization of nodes, *b*) enforced symmetry in terms of communication links for multihop routing scenarios, *c*) efficient control over connectivity and interference by adjusting the transmission power on node level, *d*) fully distributed operation, *e*) and lastly an abstraction over the real network to be used by higher layer protocols or applications.

The rest of the paper follows: In Section 2 we present the relevant state of the art. In Section 3 we describe the general motivations of our holistic approach while Section 4 covers the design details of SCLD-ATP. We continue in Section 6 with experiments and focus on link quality, load balancing, symmetry and fault tolerance, using indoor WSN testbeds. Last, in Section 7 we discuss future work, possible optimizations and application schemes.

2 RELATED WORK

Topology control protocols (Santi, 2005) use various properties of WSN nodes like transmission power and packet rate or employ schemes like duty cycling. Their goals range from network construction or maintainance with various atributes that relate to network coverage, node connectivity, link symmetry for reliable multihop communications, energy efficiency and interference minimization for specicic application scenaria and traffic load. Other schemes aim at the construction of higher level network structures like spanning trees or hierarchical clusters that inheritently achieve a subset of the above atributes (Chazelle et al., 2001; Heinzelman et al., 2000; Wang and Medidi, 2007; Blough et al., 2003; Park and Sivakumar, 2002).

We here summarize and discuss the most representative work related to this topic. Although our main interest lies within real experimental research and systems protocol design we also look at the problem of topology control from theoretical contributions where many ideas in recent studies of this field derived from. Despite the fact that related work in this field uses similar techniques and overlaps in ideas, we try to roughly divide it in two main categories. Protocols that prioritize on some degree of spatial conformity or individual link quality.

2.1 Degree Based

LINT (Ramanathan and Rosales-Hain, 2000) is a milestone attempt of distributed control, where nodes adjust their transmission powers to maintain a sufficient degree of neighboring nodes within a $[D_{min}, D_{max}]$ limit. The power setting for each node is calculated as the difference between the current power setting, to a target power setting that meets the neighbor degree demands. This is performed using a path-loss, receiver sensitivity and density model. LMA and LMN (Kubisch et al., 2003) are distributed schemes of periodic transmission power control. LMA is based on a degree of neighbor connectedness and LMN is based on a single degree of average neighbor connectedness. For both of these schemes transmission power is adjusted by a constant factor per neighbor and link symmetry is decided based on acknowledgements. The authors also comment on important problems of convergence, like exclusion of nodes from stabilized portions of the topology. DTPC (Jeong et al., 2007) performs transmission power adjustments and link qualification using a single RSSI threshold and a single degree threshold. Performance of DTPC is evaluated with experiments that focus on throughput and power consumption.

2.2 Individual Link Based

Standalone protocols like ATPC (Lin et al., 2006) and PCBL (Son et al., 2004) focus on fixating transmission powers for individual links. PCBL uses a sampling period where Packet Reception Rates (PRR) are correlated with specific transmission power settings for each link. Two PRR thresholds are used for blacklisting low quality links. ATPC uses RSSI/LQI metrics for direct link qualification. Initially RSSI or LQI are sampled with broadcast messages and verified for symmetry with acknowledgements. Then a feedback loop adjusts transmission powers for individual links, based on a least square approximation predictive model. Alternatively ART protocol (Hackmann et al., 2008) was designed as a lightweight embeddedment, where topology and neighbors are presupposed from higher level protocols. ART computes link PRR by monitoring packets exchanged from other protocols. Link filtering is based on two sliding window thresholds for failure detection correlated by two PRR values, in order to set proper transmission power.

3 MOTIVATION

3.1 Importance of Degree Limitations

Related work that prioritizes individual link quality has no internal mechanism for enforcing any spatial control over neighborhoods. We exclude ART from this critique since it was designed as lightweight embeddedment, where topology and neighbors are presupposed from higher protocol layers. As far as ATPC and PCBL are concerned, there are no limitations to the number of links created. In a dense node deployment these protocols will create redundant links between nodes, maintain local maximums in terms of neighbor connectivity and possibly subject a high number of nodes to interference. In our proposed protocol we follow a degree adherence of $[Dmin, Dmax]$ as has been provided in LINT and LMA/LMN. Although we see that DTPC uses only a *Dmin*, we believe that a *Dmax* is required for the creation of load balanced neighborhoods and could be also considered as a way of indirectly limiting interference. A constant (Hajek, 1983), (Kleinrock and Silvester, 1978), or dynamic (Xue and Kumar, 2004) number of neighbors (three, six or $\Theta(\log n)$) have been proposed in order to achieve a connected network with high probability. In our case, defining exact degree bounds was not in our scope of interest.

3.2 Link Quality

We performed a small set of experiments in our local testbed (UniGe) in the University of Geneva to verify the behavior of LQI and RSSI, compared to PRR. The testbed is currently comprised of 25 Coalesenses iSense nodes based on the 32bit Jennic JN5139 IEEE802.15.4 wireless micro-controller that supports six transmission power settings covering a $[-30, 0]$dB space, with a -6dB step interval. We conducted six experiments for every transmission power setting. In all experiments nodes booted with a random back-off timer between $[0, 1000]$ milliseconds, to avoid collisions and broadcasted 1 beacon per second, for 300 seconds. We observe (Fig. 1) that when LQI and RSSI values are sampled from a deployed network, they cannot be correlated to exact PRR values as a general rule. Also, high PRR links can exist inside the full LQI and RSSI value spectrum. Different obstacles, equipment that generate noise and temporal environmental conditions between individual links, can alter the RSSI or LQI of a considerable amount of links that hold high PRR values. In Fig. 2 we also see that link length does not correlate with specific LQI and cannot produce a clear approximation

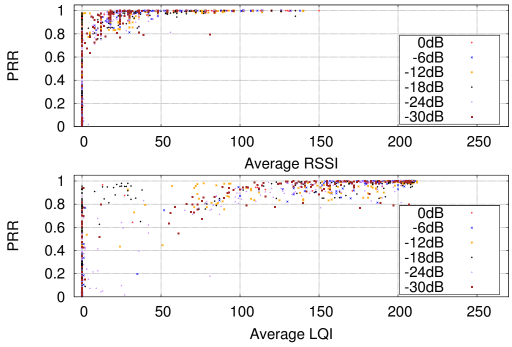

Figure 1: Link PRR versus average LQI and RSSI. Each point represents a link in a transmission power.

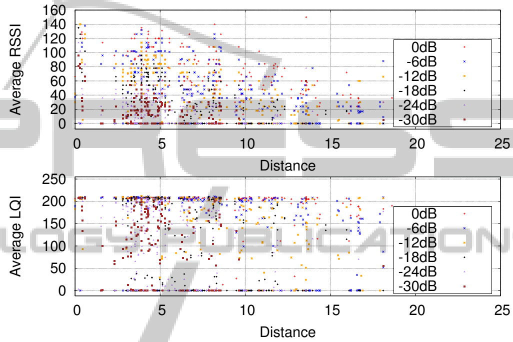

Figure 2: Average LQI and RSSI versus link length. Each point represents a link in a transmission power setting.

for RSSI values for the first 10 meters. Strategies that include certain value ranges as "close distance" links, or exclude values as "long distance" links would not be accurate. We do agree that RSSI and LQI could be correlated with specific PRR values, but only on an individual link basis and only under specific environmental conditions.

3.3 Fault Tolerance

An important aspect of topology control protocols, is the detection of abrupt changes in the topology, before they could potentially hinder the performance of higher layer protocols. For example, an unhandled node failure at an arbitrary moment in time would cause a failure for a routing scheme and maximum retransmissions, if the faulty node was chosen as the next recipient. Topology control schemes that utilize PRR as a link quality descriptor will have to update the failure through PRR convergence. If PRR is derived through a high number of accumulated messages, PRR updates per message would take a considerable amount of time in order to reflect the failure (like PCBL). In the case of ART the failure will be detected via the double sliding window of failures, but due to the embedded nature of ART, the detection will come after failure.

4 SCLD-ATP DESIGN

4.1 Link Quantification

We focus on *PRR* for link characterization, but this information does not guarantee equal behaviour on a bidirectional basis. Protocols like PCBL and ART correlate the ability for successful delivery of a message from node A to node B, to the ability of node A receiving a message from node B. ART verifies this with acknowledgements after a successful unicast reception from node A to node B. SCLD-ATP on the other hand provides nodes with their inverse PRR (*inv_PRR*). A link between node A and node B is characterized by two *PRR* values, PRR_A calculated locally in node B and PRR_B calculated locally in node A. In fact PRR_A calculated in node B is more important for node A than PRR_B, as it represents the exact capability of node A delivering a message to node B. PRR_A for node A is the inv_PRR_B of the link.

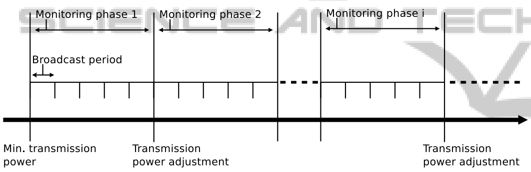

Figure 3: The online service scheme of SCLD-ATP.

4.2 Online Service

In SCLD, we follow a stand alone protocol scheme that acts as an online service (Fig. 3). Initially nodes broadcast beacon messages at a constant but also locally adjustable rate. Specifically a packet is broadcasted with a uniform random back-off timer once in every broadcast period. When nodes receive beacons from their neighbors, they store their unique ID's, update their PRR and also maintain averages for LQI and RSSI. Since the beacon rate is advertised in the broadcasts, recipients can dynamically calculate the number of expected messages that affect PRR and average RSSI and LQI. Based on user or higher protocol parameters, links with high PRR are advertised in the beacons. Specifically, nodes include the ID's as well as the updated PRR of their neighbors in their messages. Receivers that find themselves in broadcast messages, acquire these inv_PRR values and update the link information between them and the sender locally. After a predefined number of beacons that produce a stable PRR, a *monitoring phase*, the SCLD-ATP daemon kicks in and assesses quality and number of links. All links must exceed two PRR thresholds $\{Th_{PRR}, Th_{inv\_PRR}\}$ to be considered symmetric. Nodes must also contain a bounded degree of these links between $[D_{min}, D_{max}]$. If the degree of these links is lower than D_{min}, the transmission power of the node is increased by one step. If the degree of these links is higher than D_{max}, the transmission power is decreased by one step. We see this in the *Transmission power adjustment* instances in Fig. 3. After the transmission power adjustment, a new PRR is computed for all links based on an exponential moving average with a high coefficient. This also applies for LQI and RSSI averages.

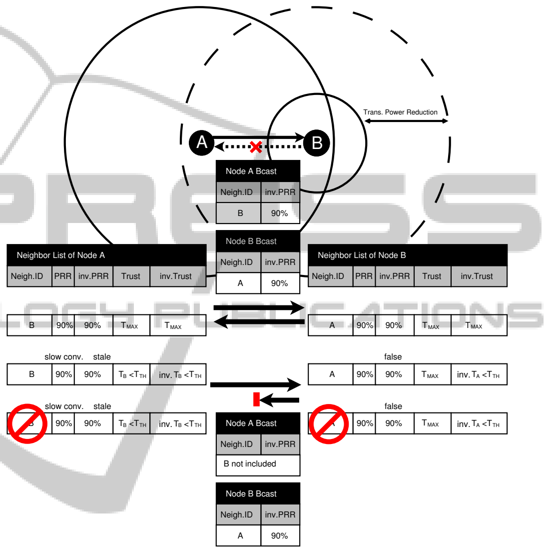

Figure 4: Loss of symmetry is detected in both sides. Neighbor B is not considered for Node A due to $T_B \leq T_{TH}$ and not included in broadcasts. Neighbor A is not considered for Node B due to $inv\_T_A \leq T_{TH}$, but included in broadcasts as fit.

4.3 Symmetric Coherent Links

Nodes in SCLD-ATP simply broadcast information autonomously, without depending on acknowledgements from other nodes. Changes that could affect the quality of symmetry in links could happen during abrupt dynamics and failures, or increases and decreases of transmission power during normal operation. PRR and inv_PRR are not sufficient enough to characterize a link in this case. In fact, a message reception or it's expectancy can always contribute towards the computation of a statistic like PRR. On the other hand, statistics regarding conditional information (like inv_PRR) within a message cannot be computed in the same way. Since inv_PRR has to be computed by a neighbor and cannot always be delivered, its value has to be characterized as trustworthy by the recipient. We will describe this necessity from the example of Fig. 4.

We see that node A maintains information about node B $\{PRR_B, inv\_PRR_B\}$ and node B maintains information about node A $\{PRR_A, inv\_PRR_A\}$. The symmetric link is stable at $\{90\%, 90\%\}$ from both perspectives. At an arbitrary moment, node B decides to reduce it's transmission power enough to sever the symmetry of the link. Node A can deliver messages normally to node B, but node B cannot deliver messages to node A and thus cannot send PRR_A to node A. In the mean time PRR_B will start to slowly converge towards the actual behaviour of node B. inv_PRR_B on the other hand cannot be updated by node A and will remain stale. Without any control of this situation, node A would still advertise symmetry to node B, until PRR_B finally gets under a minimum threshold. Since node B is always able to receive messages from node A, it will still assume symmetry in the link and will continue to maintain node A as a viable neighbor. We propose a simple and effective solution to this problem in the form of a trust based mechanism:

(a) A trust value T to regulate PRR with $T \in [T_{min}, T_{max}]$. T accumulates per successful **message**, reduces per failed delivery.

(b) A trust value inv_T to regulate inv_PRR with $T \in [T_{min}, T_{max}]$. inv_T accumulates per successful delivery of inv_PRR **information**, reduces on non delivery.

(c) A threshold $T_{TH} = \frac{T_{min}+T_{max}}{2}$

(d) A link is **symmetric** and **coherent** (**SCL**) when both $T > T_{TH}$ and $inv\_T > T_{TH}$.

Following this scheme we see that as soon as node B can't deliver messages, T_B falls below the T_{TH} threshold and the link is not considered as viable, nor it is included in the broadcast messages of node A. Node B on the other hand maintains high T_A for node A, but since there is no delivery for inv_PRR_A the link is not considered viable as well. Still, since the link is trusted to deliver information (or the knowledge of lack of information), node A is included in the broadcasts of node B. We will be referring to the degree of SCLs in a node as *SCLD*, the nodes that contain an SCLD less than the D_min threshold as *local SCLD minimums*, while the nodes that contain an SCLD higher than the D_max threshold as *local SCLD maximums*.

4.4 Spatial Control

An important choice we followed with SCLD-ATP, is to include upper and lower bounds $[D_{min}, D_{max}]$ for the links delivered (like LINT and LMA/LMN) and not a single D_{min} threshold (like DTPC). The reason lies within the fact that it is very hard for nodes to converge to an equal, exact degree threshold. In the case of our iSense nodes, the difference between two settings of transmission power is so large that a single degree threshold could cause oscillating behaviour between two transmission power settings. The low setting would never be able to achieve a degree higher than D_{min} and the high setting will always achieve a degree higher than D_{min}. Later in our experiments we will see that when degrees are unattainable, oscillating behaviour could potentially spread to all the nodes in a topology.

Unlike DTPC but similarly to TPSO, we choose to start the convergence process with the minimum transmission power setting for all nodes. In deployments where nodes boot with the maximum transmission power setting, links of various lengths are going to antagonize for a position in the limited $[D_{min}, D_{max}]$ space that their neighbors have to maintain. Since the criteria of reducing transmission power is related to the degree of high quality links, a high setting that could fullfil degree requirements for some nodes, could be unecessary. The same requirements could be achievable with some lower setting. Also starting with the lowest setting means that link qualification in monitoring phases will start with minimum interference.

An important feature of SCLD-ATP is the ability to mitigate the effects of node exclusion in converged neighborhoods. As previously discussed, a $[D_{min}, D_{max}]$ limit enforces antagonism on links. Since we start with the minimum transmission power on all nodes, we always **favor** the shortest available links. This introduces problems in terms of the general connectedness of the topology and more specifically introduces node exclusion. For example, a network could contain disconnected nodes. Normally these nodes will start increasing their transmission power in order for their beacons to be discovered by other nodes. If all the recipients have converged to their SCLDs with a relatively low transmission power setting, they will show no interest in increasing their transmission power any further. Thus, excluded nodes could continue being excluded from participating in symmetric and coherent links. To mitigate this effect, all nodes advertise their SCLD in their beacons. A receiving node stores this information for all links and before each beacon, the links maintained by a node are sorted by their advertised SCLD. Priority is given to the first D_{min} number of links with the **least SCL Degree**. Transmission power could then be increased further, to serve the "most desperate" nodes first. With this technique, the priority of maintaining shortest links can be overridden by the presence of excluded or less connected nodes.

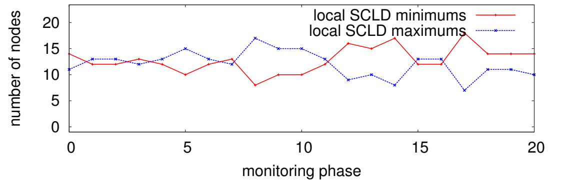

Figure 5: Oscillating SCLD local minimums and maximums. Stabilization is impossible when a narrow [2, 3] SCLD range is chosen.

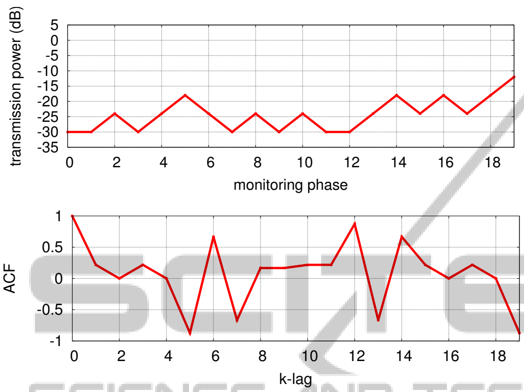

Figure 6: Oscillation detection on a single node. From feedback setting as a discrete time series, to normalized correlogram and in the end, peak detection.

4.5 Feedback Oscillations

This problem of oscillations in transmission power was initially observed after the duration of experiments by sampling the networks number of local SCLD minimums and maximums for each monitoring phase. As seen in Fig. 5, oscillations could potentially affect the complete topology. In order to mitigate their effects, we first had to detect them at a node level.

We use a rolling history window for both transmission power adjustments and correlated SCLD values and treat them as discrete time series with samples taken every monitoring phase. When the history window of transmission power adjustments is full (ten samples in our case), we perform an autocorrelation. This local computation takes place on every monitoring phase and is normalized by mean and variance for a five sample frame. In this way a temporary correlogram can be produced on memory. By detecting peaks inside this correlogram, we can expose cases of hidden periodicity. Any autocorrelation coefficient higher than two times the variance of the history window, is considered a peak. Fig. 6 shows the transmission power adjustments of a single node in the topology when an oscillating behaviour occurs. When three or more peaks are detected, we simply increment D_{max} and decrement D_{min}. Nevertheless, not all oscillations are problematic. During convergence, nodes might oscillate between high and low settings until they stabilize, as seen in the local SCLD minimums/maximums graph from Fig. 18. SCLD-ATP only regulates the oscillations that show a non stabilizing behaviour, signified by peaks in the corellogram that either have *monotonous increasing* or *constant* absolute values.

5 IMPLEMENTATION

We implement our protocol using Wiselib (Baumgartner et al., 2010): a code library, that allows implementations to be OS-independent. It is implemented based on C++ and templates, but without virtual inheritance and exceptions. Algorithm implementations can be recompiled for several platforms and firmwares, without the need to change the code. Wiselib can interface with systems implemented using C (Contiki), C++ (iSense), and nesC (TinyOS). Additionally, Wiselib also runs on the simulator Shawn (Fekete et al., 2007) and TOSSIM (Levis et al., 2003), hereby easing the transition from simulation to actual devices.

SCLD-ATP is designed (Fig. 7) as two closely-coupled software modules. The first module, named **SCL**, is responsible for: *a*) performing the periodic broadcasts, *b*) maintaining and updating neighborhood lists, *c*) filtering links based on thresholds, *d*) providing an API for dynamic threshold updates. The second module, named **ATP** acts as a daemon that periodically accesses and assesses the neighborhood list of SCL module. Based on the quality and quantity of links, the transmission power is increased, decreased or remains constant.

Our implementation is also based on the Unifying Link Abstraction Layer (Polastre et al.,) principle and Wiselib's Topology Control Concept. We thus provide an abstract interface for interaction and asynchronous communication with the established topology that other developers can use to implement their own protocols without hassle. In more detail, SCLD-ATP acts as intermediate service between the actual hardware radio communication and higher layer protocols and applications. Using Wiselib's generic callback mechanisms other protocols can register and receive notifications and information whenever the topology is altered.

Additionally we offer a reliable broadcasting mechanism for message exchanges over the established neighborhoods. This mechanism takes advantage of SCLD-ATP's periodic beaconing process and piggybacks external payloads on its messages.

As a result other applications including clustering, grouping or tracking can be implemented with less dedicated message exchanges, reducing both the network traffic and energy consumption.

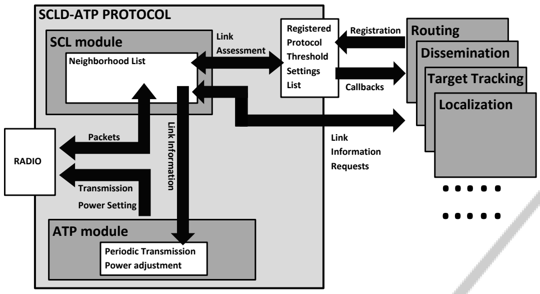

Figure 7: SCLD-ATP modular and interactive design. High layer protocols can register for callbacks to receive updates and also access link information on demand.

5.1 State of the Art Implementation

We have also implemented the degree based protocols discussed in Section 2.1, namely DTPC (Jeong et al., 2007), LINT (Ramanathan and Rosales-Hain, 2000) and LMA/LMN (Kubisch et al., 2003). As far as DTPC is concerned, implementation was simply a choice of parameters and optimizations being disabled. Since LMA/LMN were theoretical protocols, we deviated from their design in favor of implementation. Instead of using the two distinct packet types for symmetry (for every broadcast message all receivers must send acknowledgement packets), we used our single beacon packet scheme and included the LMN heuristics for average neighbor connectedness.

LINT, also a theoretical scheme, was designed for instant and not incremental transmission power adjustments based on a path-loss model. We first implemented a log-normal shadowing model (Stojmenovic et al., 2005), for fast computations of the probability of reception PR_S and parameterized it to match the capabilities of our iSense nodes, with six different transmission power settings. For the distance to transmission power correlation we used a simplification of the Friss free range propagation model (Rappaport, 1996) where $R = 50 \cdot 10^{\frac{P_{TX}}{20}}$. We have also added a uniform random irregularity factor $r_f \in [0, 0.15]$ such that $PR = PR_S(1 - r_f)$, as seen in Fig. 8. The beacon packet was also updated so that nodes include their transmission power setting in dB.

A node running the LINT protocol starts increasing its transmission power until it acquires a number of neighbors bounded by $[D\_min, D\_max]$. Then, it performs a quick-sort on its neighbor list based on PRR. If the PRR of the $(D\_min)th$ neighbor is below a certain PRR threshold, it approximates its distance using its advertised transmission power setting from the radio propagation model. Then, it finds the lowest transmission power setting for packet delivery above the PRR threshold, at that given distance. Since transmission power is increased to meet the demands for the node with the lowest PRR (and thus the more distant), it will also cover the demands of the first $(D\_min - i)th$ neighbors.

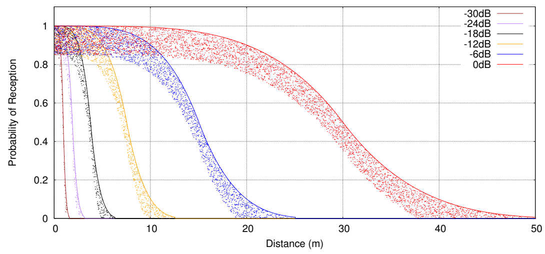

Figure 8: Log-normal shadowing model for LINT implementation.

Table 1: The broadcast packet of SCLD-ATP.

Data	size in bytes
Message ID	2
Node ID	2
Beacon Rate (ms)	2
Symmetric Coherent Link Degree	1
Length of neighborhood list (bytes)	1
Length of custom payload list (bytes)	1
Neighborhood list	
Node ID	2
inv_PRR	1
average inv_LQI	1
average inv_RSSI	1
....	
Custom payload list	
length of custom payload (bytes)	1
custom payload	variable
....	

5.2 Constrained by Resources

The size of the final binary file we flashed in our iSense nodes was approximately 60KB for all cases. With 40KB for the standard firmware including the WISELIB interface instances (such as Radio, Debug, Rand, Clock, Timer), 14KB for the SCL module and approximately 4KB for the ATP module. Each entry in the neighborhood list maintained in the SCL module is 24 bytes, while a single entry for the registered protocol buffer occupies 17 bytes without any additional custom payload data. For a topology of 25 neighbors and 1 registered protocol we had to allocate less than 1KB of memory.

As far as the packet size is concerned (Table 1), based on the maximum size of 116 bytes we use a header of 9 bytes. Each symmetric trusted (SCL) neighbor occupies a maximum of 5 bytes with a maximum of 21 neighbors per packet, or 3 bytes if we exclude average inverse MAC metrics with a maximum of 35 neighbors per packet. If protocols register with custom payloads, less neighbors are going to fit inside a single packet. Threshold limitations on link quality in conjunction with the **least SCLD** optimization could further reduce the need of occupying valuable packet space.

6 REAL EXPERIMENTS

For our real device experiments we used the testbeds of the WISEBED flexible experimentation framework (Coulson et al., 2012). UniGe previously discussed in Section 3 and CTI testbed (Computer Technology Institute and Press University of Patras) that contains 11 iSense nodes. We assess the performance of our protocol and compare it to the state of the art in terms of:

- Network consistency. A topology that maintains a minimum number of local SCLD minimums/maximums is load balanced, fault tolerant and harder to partition.
- Average transmission power of the topology, as a factor of power consumption and interference.
- Multi-hop performance. At the end of each experiment we inject 10 agent-packets that perform a random walk in the topology using a 2-max retransmission scheme. We consider a protocol suitable for multi-hop strategies when the average number of agent hops is above 5000.

The experiment settings were: a $[4,6]$ degree range, *PRR* and *inv_PRR* thresholds at 90% and trust thresholds $[T_{min}, T_{max}]$ at $[0,6]$. All nodes broadcast one packet per second and boot from the minimum transmission power setting $(-30dB)$, unless stated otherwise. Each monitoring phase lasts for 20 seconds.

6.1 DTPC Performance

In order to recreate DTPC with our design, we disabled average RSSI and average inv_RSSI filtering (replaced by the newest received values), oscillation detection, as well as the the *D_max* upper bound. A node adjusts its transmission power based on a single threshold of $(D\_min + D\_max)/2$.

We conducted various experimental runs for DTPC and chose to initially report results based on two RSSI threshold settings. The first setting considers links with $RSSI \geq 20$ and $inv\_RSSI \geq 20$ and produces a topology that maintains an average transmission power setting at approximately $-20dB$. The second setting considers links with $RSSI \geq 50$ and $inv\_RSSI \geq 50$ to ensure that all links maintain a *PRR* and *inv_PRR* above 90% based on Fig. 1.

Results presented in Fig. 9 show that the DTPC-20 considers many links of questionable performance that result in an average link degree around 8 for the topology. Fig. 10 shows that the topology maintains a high number of local degree maximums. Agents injected later, couldn't complete the first 5 hops in their traversal. DTPC-50 on the other hand showed an average link degree close to the *D_min* threshold with increased transmission power around $-10dB$. Still, Fig. 11 shows a continuous high number of local degree minimums and maximums and similar poor performance in multihop attempts. Further investigation showed great instability and oscillations on individual node level. Both cases are problematic because: *a*) RSSI cannot correlate to a specific PRR value accurately. Thus symmetry using plain RSSI values doesn't correlate to true symmetry. *b*) Transmission power adjustments as well as normal beaconing operations can cause high RSSI fluctuation. *c*) A single degree threshold that is unatainable on the lowest transmission power adjustment difference, will cause oscillations that could extend to other nodes (Fig. 11). For the last experiment in this set, we enhanced DTPC to support averages for *RSSI*, *inv_RSSI* as well as symmetric trust. We kept the average RSSI threshold at 50. Results in Fig. 12 coincide with Fig. 1. This time many links of good PRR performance are not considered for this RSSI threshold even with all nodes transmitting at maximum setting $(0dB)$. Alternatively all agents performed well above the 5000 hops, trapped in the lower section of the topology.

6.2 LINT/LMA/LMN Performance

Conducting experiments with LMA/LMN produced poor results on on all aspects resembling the case of DTPC-20 in Fig. 10. Since we were further interested in the heuristics of LMN, we enhanced it with the SCL qualification criteria. Nodes running the LMN+ protocol increase or decrease their transmission power based on the average SCLD of their neighbors, thus we treated the SCLD threshold as the average SCLD of neighbors threshold. Subsequent results in Fig. 13, 14 showed an extremely low average transmission power setting for the topology, approximately one third of the network nodes as local SCLD minimums as well as

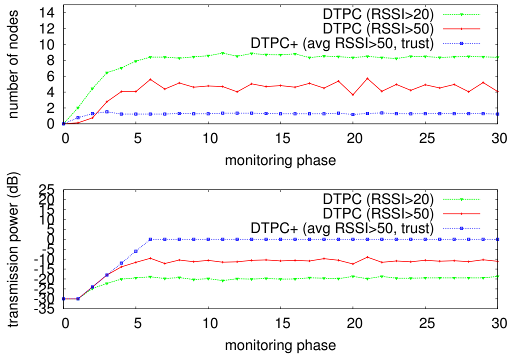

Figure 9: Average Degree for DTPC, average SCLD for DTPC+ and average transmission power for the different RSSI/trust settings.

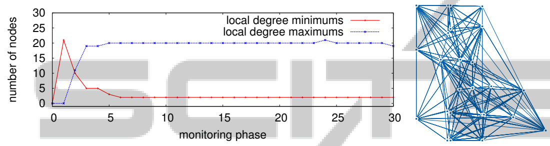

Figure 10: DTPC: Local degree minimums/maximums and link graph at 30th monitoring phase, with $RSSI \geq 20$.

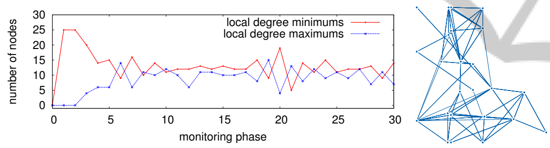

Figure 11: DTPC: Local degree minimums/maximums and link graph at 30th monitoring phase, with $RSSI \geq 50$.

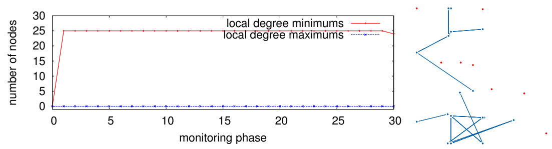

Figure 12: DTPC+: Local SCLD minimums/maximums and SCL graph at 30th monitoring phase, with $AVG\_RSSI \geq 50$ and symmetric trust.

some nodes being completely disconnected from the topology. Nevertheless, the SCL provisions allowed agents to traverse successfully with an average number of hops above 5000.

For LINT, all notions of link symmetry were disabled. Results showed very good performance for degree convergence and low average transmission power (approximately -20dB) for the topology. Still all agents could not complete the necessary number of hops. Upon enabling SCL provisions, LINT+ maintained a performance of SCLD convergence with multihop attempts fulfilling an average 5000 hops. The trade-off was an increase in the average transmission power (-15.2dB) and few local SCLD maximums.

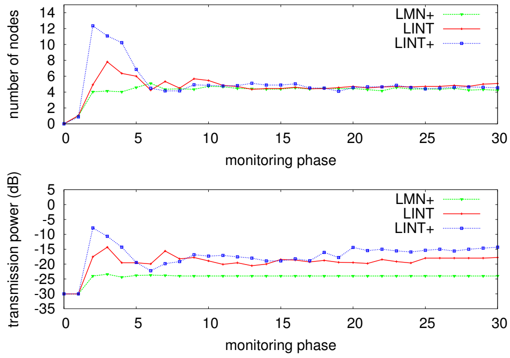

Figure 13: Average Degree for LINT, average SCLD for LINT+/LMN+ and average transmission power.

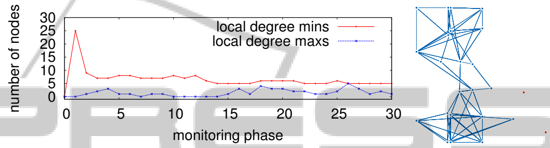

Figure 14: LMN+: Local SCLD minimums/maximums and SCL graph at 30th monitoring.

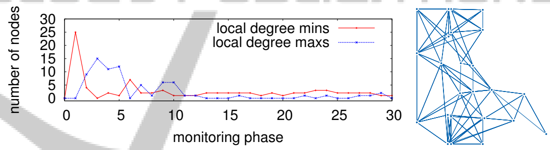

Figure 15: LINT: Local degree minimums/maximums and link graph at 30th monitoring phase.

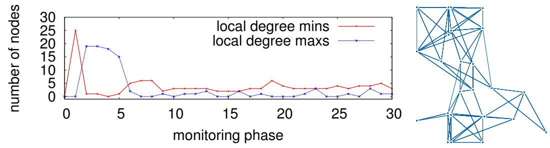

Figure 16: LINT+: Local SCLD minimums/maximums and SCL graph at 30th monitoring phase.

6.3 SCLD-ATP Performance

We performed three runs for SCLD-ATP. On the first run, nodes boot with the maximum transmission power (0dB), on the second run with the minimum transmission power (-30dB) and on the last run, nodes boot with a random transmission power setting.

In Fig. 17 we see that all variations produce very similar results as they converge to the same average SCLD well inside the $[D_{min}, D_{max}]$ range. Random and minimum transmission power boot settings maintain a low average transmission power at $-20dB$ while the maximum transmission power boot setting maintained a $-16.2dB$ average setting. Local SCLD minimums and maximums also tend to become minimal in Fig. 18 19, 20. Multihop performance was also successful with

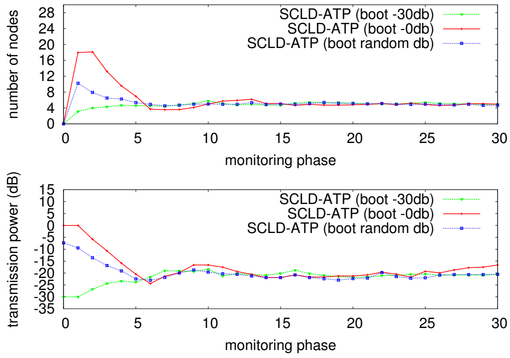

Figure 17: SCLD-ATP: Average SCLD and average transmission power for different boot settings.

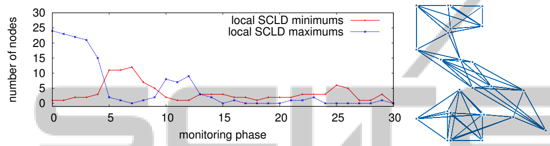

Figure 18: SCLD-ATP: Local SCLD minimums/maximums and SCL graph at 30th mon. phase, booting from 0dB.

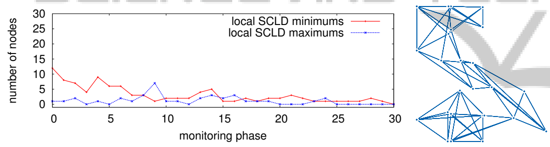

Figure 19: SCLD-ATP: Local SCLD minimums/maximums and SCL graph at 30th mon. phase, booting from -30dB.

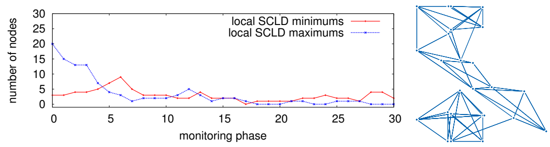

Figure 20: SCLD-ATP: Local SCLD minimums/maximums and final SCL graph, booting from a random setting.

agents performing above 5000 hops on all cases.

From comparisons we see SCLD-ATP outperforms DTPC. At an equal average transmission power setting of approximately $-20dB$, DTPC fails to maintain a low number of local degree minimums and maximums and performs poorly in multihop attempts. With a higher RSSI filtering DTPC fails similarly with additional oscillations. Even when an average RSSI threshold guarantees links of high quality (DTPC+), it filters out a significant amount of links that do indeed perform well but are not correlated accurately to RSSI.

Comparing the performance of LMN+ we see that it does operate at a lower transmission power setting at $-24dB$ but the heuristics used tend to make nodes not care about their degrees and result in a significant number of local SCLD minimums as well as nodes being completely excluded. Running LINT without any SCL provisions performed poorly in multihop attempts. LINT+ showed good results on all levels as it maintained low local SCLD minimums/maximums, excellent multihop performance and an average transmission power at a $-15dB$ margin, closely related to the innability of the path-loss model to describe accurately properties of different links. Still, the default setting of SCLD-ATP (boot at $0dB$) results in an average of $-20dB$, a scale lower.

Since our hardware nodes didn't support energy monitoring, we coupled one node with a battery sensor and an AA battery ($2250mAh$) and programmed it with version of SCLD-ATP to run at fixed transmission power settings. The node was reporting battery capacity statistics via broadcasts and was subjected to 8 packets per second. A second node that provided the packets was receiving and logging statistics. Hourly operations showed linear battery drain of $39750uAh$ at $-30dB$, $40125uAh$ at $-24dB$ and $40250uAh$ at $-18dB$. A WSN topology running SCLD-ATP with single AA batteries on iSense nodes, at an average $-20dB$, without any duty cycling scheme could last for approximately 55 hours of continuous operation.

6.4 Topology Repair and Fault Tolerance

Here we show how a disconnected network could be repaired and secondly, the ability of the SCLD-ATP protocol to recover from abrupt node failures. First, we try to create a scenario of disconnectedness through convergence. We perform our tests using the CTI testbed but enforce a $[2,3]$ SCLD limit and run the experiment for 60 monitoring phases. At the 30th monitoring phase we enable a middle-node between these neighborhoods. As seen in Fig. 21, the topology is divided into two disconnected neighborhoods. Nodes in these neighborhoods have sufficient SCLDs and have no interest whatsoever to increase their transmission power further. Since the newly introduced node has no SCLs, it advertises a SCLD equal to zero in its broadcasted beacons. As soon as the middle-node becomes trusted to its *unwilling to connect* neighbors, its SCLD is treated with higher priority due to the **least SCL** optimization. At latter, phases SCLs are regulated again based on the $[D_{min}, D_{max}]$ thresholds with the excessive SCLs destroyed. In the end, the topology stabilizes with a low number of SCLD local minimums and maximums and a stable average transmission power setting (Fig. 22).

We continue with our next experiment in the UniGe testbed. The number of monitoring phases is set to 60 and all the nodes start from the minimum transmission

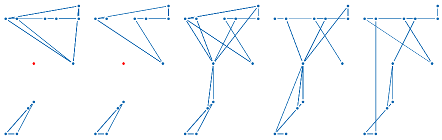

Figure 21: SCL graph transition, before and after enabling middle-node.

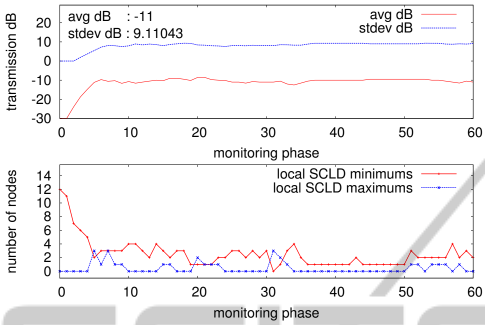

Figure 22: Average transmission power and local SCLD minimums/maximums booting from 0dB.

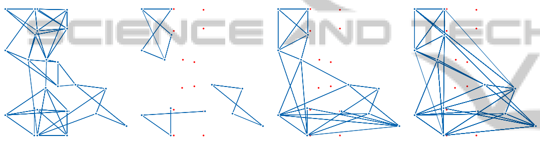

Figure 23: SCL graph transition, before and after disabling middle section.

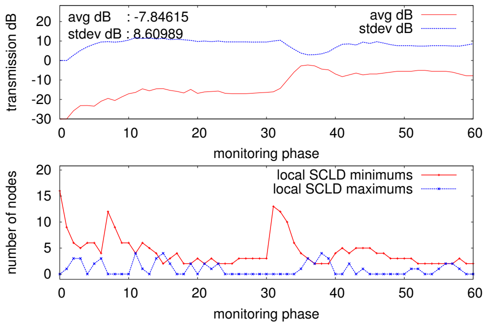

Figure 24: Average transmission power and local SCLD minimums/maximums booting from 0dB.

power setting with a [4,6] SCLD range. At the 30*th* monitoring phase we shut down 12 nodes in the middle section. From Fig. 23 we observe that nodes initially form an SCL connected topology until the 30*th* monitoring phase. Then, the selected nodes are disabled and the topology is divided. After three monitoring phases, the network resumes an adequate SCLD within the predefined range and remains stable. Since the disabled nodes split the topology to distant parts, new SCLs have higher lengths and correlate to higher transmission powers, thus reflecting the average transmission power increase (raised by 10dB). Lastly, local SCLD minimums and maximums stabilize in low numbers with a spike of local minimums at the 31*st* monitoring phase (Fig. 24)

7 CONCLUSIONS AND FUTURE WORK

In this paper we have presented SCLD-ATP, a topology control protocol with adaptive transmission power adjustments that operates as a ubiquitous service. Its main functionality is to create, maintain and constantly update a load balanced, stabilized network for low transmission power operation, that maintains multihop capabilities. It also provides a general network abstraction, so higher layer protocols can be updated via callbacks or on-demand requests for link information. Through various experiments we show that SCLD-ATP can tackle many inherent problems of WSNs such as unreliable and asymmetric links, network instability and unpredictable events.

We wish to extend our proposed protocol for adaptive throughput control, perform further experiments with mobile nodes and test it in conjunction with other protocols like routing or target tracking. Other ideas include heuristics for transmission power adjustment on neighborhood weighted local SCLD minimums and maximums minimization.

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