Cross-Layer Proactive Hybrid MAC to Prolong Lifetime of Wireless Sensor Networks

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Abstract—A fundamental design challenge in energy-constrained wireless sensor networks is to maximise the operational time. With increasing node density and multi-hop communications, disproportion on traffic intensity and congestion level among nodes leads to uneven battery consumption and thus the existence of failure-prone nodes. Common fault-tolerant schemes focus on routing strategies although the effectiveness of rerouting is limited by the congested medium where failure-prone nodes are located. We propose a localised proactive hybrid medium access control (MAC) approach (Pro-SSAS), where nodes that are expected to be failure-prone are enhanced with scheduling access from their senders to avoid being active during the energy-expensive contention periods. Cross-layer techniques are implemented to detect failure-prone nodes and to adapt the MAC operation. Realistic simulations have verified that Pro-SSAS significantly prolongs overall network lifetime compared with rerouting schemes.

I. INTRODUCTION

In light of the limited energy supply, a main goal of wireless sensor network (WSN) design is to maximise the network lifetime whilst meeting the application requirements. S-MAC [1] revolutionarily introduces duty cycles, periodically putting active nodes into sleep to save energy. Nevertheless, congestion remains a major threat to network health for contention-based medium access control (MAC) such as S-MAC, especially in multi-hop nodes-to-sink applications [2]. Nodes closer to the sink become more saturated from heavier data forwarding task, and thus tend to deplete their batteries notably faster, terminating the network operation once they have failed as the sink becomes isolated.

Typical techniques for failure recovery are reactive rerouting schemes [3], diverting the traffic to alternatives routes, if possible, after failure detection. Unfortunately, rerouting can degrade the overall network performance by deteriorating alternative routes with additional congestion. The more attractive yet challenging failure management approach is to proactively detect potential failures and adapt the network communications to prevent or postpone the failure. Consequently, the network usability can be extended.

A natural solution is balancing routing where the senders of failure-prone nodes distribute traffic load among their next-hop receivers. However, as demonstrated in a recent work [4], typically network redundancy is needed and the detection of failure-prone nodes is based on global knowledge of specific metrics such as the neighbours’ battery levels, which implies extra overhead from the information sharing among nodes.

To overcome the restrictions of the discussed solutions, we have been investigating MAC designs to minimise the active time, reduce sources of congestion, adopt adaptive schemes to avoid waste of resources and offer proactive solutions for the failure-prone nodes. The first scheme called Scheduled Sectorial Access at Sinks (SSAS) [5] increases the network lifetime by reducing the congestion at the sinks with scheduling access from one-hop nodes compared with S-MAC. Optionally, the sink can benefit from directional antenna capabilities to extend the profit of scheduling access at the one-hop area. This paper presents an important extension to SSAS with the implementation of a localised proactive hybrid MAC (Pro-SSAS), whose target is to detect and extend the lifetime of the most energy-vulnerable nodes that seriously restrict the network operational time. Cross-layer interactions among the routing, MAC and physical layers are explored to locally predict energy-vulnerable nodes and trigger a proactive scheme. The adaptive MAC operation in failure-prone nodes that form a time division multiple access (TDMA) cluster with their senders enables them to remain sleeping during the contention periods. A balancing routing alternative is also implemented to compare with Pro-SSAS.

The remainder of the paper is organised as follows. Section II describes the methodology for failure-prone nodes detection using novel cross-layer energy metric. Pro-SSAS is then depicted in Section III. In Section IV, both the proposed metric and schemes are verified and evaluated through simulations. Section V concludes the paper.

II. PREDICTING FAILURE-PRONE NODES

A. Metric

Well-defined effective metrics to identify the failure-prone nodes in advance are essential for failure prevention. In order to evaluate the actual repercussion of the channel accessibility and network traffic in the rapidity of battery discharge, we propose a cross-layer metric called battery index (BI), which measures the effective use of the radio device, and is found to be an accurate method to predict energy-vulnerable nodes:

\[
BI = K \times \frac{w_{tx} \cdot T_{tx}(t) + w_{rx} \cdot T_{rx}(t) + w_{idle} \cdot T_{idle}(t)}{T_{sleep}(t) \cdot D_t},
\]

where \(T_{tx}(t), T_{rx}(t), T_{idle}(t)\) and \(T_{sleep}(t)\) are the accumulated time of the Transmit (Tx), Receive (Rx), Idle and Sleep modes in period \(t\), respectively; \(D_t\) the duty cycle (the ratio of active time to the total of sleep and active time in a frame);
w_{Rx}, w_{Rx}, and w_{idle} the power consumption per time unit for Tx,Rx and idle modes, respectively; K a constant scaling factor. Fig. 1 shows the instant current consumptions and transition times of the different states of the extensively used CC2420 [6] off-the-self transceiver. (Table I lists other selected parameters from the physical and MAC layers used in the simulations to verify the effectiveness of BI later.)

Since very low duty-cycles are used in WSNs, the divisor part of (1) is representing the network active time, thus BI reflects which portion of the time is used in the costly radio states. Generally, the higher the BI is, the faster a node fails. An advantage of this metric is that it explicitly takes into consideration and thus adapts to different duty cycles, which is a fundamental characteristic in WSNs. Secondly, the value of the metric remains sufficiently stable after the network initialisation stage. Thus, this metric, together with a proper predefined threshold, is very useful to allow a node itself to judge if it is likely to be a vulnerable node at the beginning of its operation without any global knowledge of the battery levels of the other nodes including its neighbours.

B. Assessing Vulnerability

To design cross-layer proactive schemes to circumvent the vulnerability from unfair battery use, analyses of the network conditions are needed. Since SSAS has largely reduced the impact of idle listening [5], vulnerable nodes are mainly determined by congestion level together with traffic load, which are closely related in contention-based MAC. Ultimately, highest BIs in the network are found in nodes that have heavy traffic and are located in congested areas, especially in those that are close to the sink.

The lifetime of these vulnerable nodes may be prolonged through routing or MAC techniques. Intuitively, traffic balancing routing strategies applied at their senders may reduce traffic load at these nodes. Alternatively, adapting the MAC operation of both these vulnerable nodes and their senders may alleviate the congestion level. In either approach, tradeoffs and implications to the rest of the network need to be assessed to choose an optimal proactive scheme. For example, if distributing the traffic destined to a vulnerable node implies a load increase in another vulnerable node, the solution can actually deteriorate the network usability.

Since radio communication is the dominant energy consumer, the focus of our work is to improve the radio usage efficiency at the MAC layer. We advocate a hybrid MAC approach that combines the strengths of contention-based MAC and TDMA MAC to provide vulnerable nodes with collision-free access from senders. The pure TDMA MAC approach could avoid contention although it is impractical in that the required tight synchronisation is not scalable. In contrast, pure contention-based MACs are scalable yet they can suffer from severe collision. Therefore, as a trade-off, the extension of the proactive TDMA in Pro-SSAS is applied only in the most vulnerable nodes. Results in Section IV will show the superiority of the hybrid MAC against reactive and proactive routing schemes.

III. Pro-SSAS: PROACTIVE SCHEMES

The proactive routing and MAC schemes presented in this section are implemented on top of SSAS. These schemes are enabled and triggered by the cross-layer information exchange measuring the radio usability (BI).

A. Baseline Routing/MAC: SSAS with Reactive Rerouting

We have defined a baseline solution [7], which is a reactive rerouting scheme to sustain the network operational time by enhancing the network resilience after nodes start to fail. A neighbour node is deemed as dead if it does not reply a number of consecutive RTS (Request To Send) messages sent to it or it has not been heard for a predefined period. A rerouting is then triggered to select the next node in the routing table as its next-hop neighbour. In the following, we propose proactive solutions enabled by BI.

B. Proactive Balancing Routing

To compare with the proactive hybrid MAC approach, we also design a dynamic routing scheme alleviating the traffic load towards vulnerable nodes. The routing protocol has the traffic loads originally destined to a vulnerable node shared by its neighbour(s). At the vulnerability checking time (VCT), every node checks its own BI; if its BI is greater than the predefined threshold, the node considers itself as a vulnerable node and then triggers the vulnerability solution. A vulnerable node notifies its neighbouring senders of its vulnerability through local signalling. Piggybacking in CTS (Clear To Send) messages using a status control bit is implemented here. Informed senders, for each RTS-CTS-DATA-ACK (RCD) round, will select the next “best” hop in the routing table with a probability p.

C. Pro-SSAS: Proactive Hybrid MAC

The application of hybrid MAC techniques is based on the natural traffic conditions in multi-hop networks with scheduling contention-based MACs such as S-MAC. In SSAS, a contention MAC is used to deliver the packets during the active time from the whole network to the one-hop nodes, which can then act as sinks receiving and buffering the packets. During the forwarding period, the one-hop nodes send their buffered packets in a burst to the sink in the specific slot assigned, which is updated at every frame with the schedule table packet (ST) sent by the sink (see Fig. 2b/d). Without the need to compete for accessing the sink, congestion problems at one-hop nodes are extremely reduced as shown in [5].
Further to the SSAS improvements with scheduled access to sinks, Pro-SSAS attempts to reproduce this concept in the most vulnerable nodes, which are most likely to be one or two hops away from the sink. Swapping to TDMA access enables vulnerable nodes to remain sleeping during the contention active periods and also reduces congestion at their senders.

The implementation of Pro-SSAS is illustrated in the Fig. 2. Fig. 2(a) shows a network portion with one- and two-hop vulnerable nodes. The proactive scheme is performed autonomously, locally and hierarchically up to three hops from the sink in the current implementation although this approach can be further extended. In Pro-SSAS, a two-hop node can not start the proactive scheme if its parent one-hop is not vulnerable itself. A two-hop vulnerable node can not remain sleeping if it needs to contend during the active time to forward the packets to its non-vulnerable one-hop parent node. However, since the one-hop node experiences at least the same amount of traffic as its senders do and both have similar congested channel in the neighbourhood, the above scenario is unlikely to happen. Hence, the TDMA enhancement is started at different VCTs as shown in the time line of Fig. 2(b) and described in the pseudo code in Fig. 3.

As mentioned, Pro-SSAS will significantly change the congestion conditions of the vulnerable nodes as well as the whole neighbourhood and even further hops. The update time enables the traffic and congestion conditions, and thus the BI, to stabilise after the adoption of TDMA access. An amount of over 10 frames have been found sufficient in simulations, yielding better results if shorter update periods are used. The slot assignation to the senders is informed in the scheduling table (ST), which is sent every frame before the data forwarding to keep synchronisation with senders. Initially, the slots sizes are given to each sender regarding the tracked average packets received from these. Fig. 2(d) shows the frame timeline events of vulnerable nodes 1 and 2 after VCT-1 and VCT-2.

IV. NUMERICAL RESULTS

A. Simulation Environment and Setting

The proposed schemes A, B, and C have been implemented in the OMNeT++ 3.4b2 simulator [8]. Particularly, the Publish and Subscribe paradigm in the Mobility Framework was exploited to achieve cross-layer signalling to expose the BI metric to interested layers. We employed realistic models for wireless channel, antenna, battery, and radio communication (based on CC2420 chip), as detailed in [5]. In the simulations, random networking topologies were generated to represent real-world deployments. Two different configurations with one sink located in the centre and the same density of nodes are considered: 100 and 150 nodes uniformly distributed in an area of 500m by 500m and 610m by 610m, respectively. One of the simulated topologies is demonstrated in Fig. 4, where • stands for a one-hop node, and circled nodes are vulnerable.

![Fig. 2 Time diagram of Pro-SSAS](image-url)

![Fig. 3 The pseudo-code of Pro-SSAS](image-url)
B. Results

1) Verification of the Battery Index and Pro-SSAS

Fig. 5(a) illustrates the evolution of the nodes’ BI and correlated lifetime in the WSN shown in Fig. 4 using SSAS, and Fig. 5(b) proves the beneficial impact of Pro-SSAS on the BI and thus the lifetime of the 10 vulnerable nodes marked in Fig. 4. The end of the BI curves represent the node dead time after battery depletion. Fig. 5(a) demonstrates the effectiveness of BI to identify the vulnerable nodes. The effectiveness has been validated under various topologies and traffic conditions. With the proactive hybrid MAC Pro-SSAS being applied at the different VCTs, Fig. 5(b) shows how the BIs at the vulnerable nodes are reduced and consequently the lifetime is increased to more than double in some cases. The beneficial impact of Pro-SSAS scheduling transmissions is also appreciated in the vulnerable nodes’ senders and the diminution of congestion is spread along the whole network. As displayed in Fig. 5, the average BI of the entire network is reduced by half whilst the average network lifetime is increased to double. Two additional performance criteria have been investigated. One is the time when the first node dies, which is commonly defined as the network lifetime in the literature. The other criterion, network resilience, is defined as the period from the moment when the first node dies to the moment when the packet delivery ratio consistently drops below 50% (when the network is considered unusable). Note that the initial battery capacity in all scenarios is set to 300 mA·s only to speed up the simulations. In reality the typical value is 3000 mA·h, and thus every second actually represents 10 hour in the following numerical results (the corresponding days are noted in the parentheses).

Simulations have been conducted in various randomly generated network topologies and significant improvements in nodes’ lifetime and network usability (packet delivery ratio perceived at the sink) have been repeatedly observed. Fig. 6 demonstrates a case study of the instantaneous data delivery ratio in the concerned systems when nodes run out of battery one by one in the network shown in Fig. 4.

As shown in Fig. 6, with the gradual deaths of the nodes, the data delivery ratio in each system decreases generally despite the fluctuations due to the nature of a WSN. The decrease is sharp during the deaths of the first few nodes, and that is why that the lifetime of a WSN is commonly defined as the lifetime of the first dead node. Definitely, the nodes’ lifetime in SSAS and its variants are by far longer than that in S-MAC due to the hybrid MAC approach used in SSAS [5]. Note that the huge time gap between 600 s (250 days) and 1300 s (542 days) is omitted in Fig. 6 for presentation purpose.

2) Evaluation and Comparison of Proactive Schemes

Through further simulations, we have evaluated and compared four systems: S-MAC [1], SSAS with reactive routing, SSAS with proactive balancing routing (SSAS+Balancing), and SSAS with proactive hybrid routing (Pro-SSAS). Note that the comparison of S-MAC and SSAS without reactive or proactive schemes is reported in [5]. The default routes are established through the one phase pull directed diffusion routing mechanism. Periodic traffic is generated towards the sink and the packet inter-arrival time is 20 s. The duty cycle in all the SSAS systems is 1.5% whilst 5% has to be used in S-MAC to match the data delivery performance with that in SSAS (>90% as application requirements). In the balancing routing, the routing scheme of a vulnerable node’s sender selects the vulnerable node with $p = 0.7$. Note that the initial battery capacity in all scenarios is set to 300 mA·s only to speed up the simulations. In reality the typical value is 3000 mA·h, and thus every second actually represents 10 hour in the following numerical results (the corresponding days are noted in the parentheses).
Among the SSAS systems, Pro-SSAS shows the best performance. Compared with SSAS and SSAS+Balancing, Pro-SSAS prolonged the lifetime of the first dead node by 120% and 160%, respectively. A 350% network resilience improvement was achieved with Pro-SSAS compared with SSAS. Balancing routing only managed to slightly alleviate the energy consumption in vulnerable nodes, and thus these nodes remain being the first nodes to die. This explains the sharp drop of data delivery of SSAS and SSAS+Balancing in Fig. 6 since the vulnerable nodes are participants of forwarding most of traffic towards the sink. Inefficiency of the reactive scheme is also observed. Success of rerouting is not guaranteed and the degradation of alternatives routes does not always compensate the actual increment of data delivery achieved at the sink. Alternatively, the hybrid MAC approach with TDMA access at vulnerable nodes significantly improves the usability in Pro-SSAS, being 90% and 70% higher than SSAS and SSAS+Balancing, respectively, as shown in Fig. 6.

In Table II, the average of important performance values of the proposed schemes are compared in network topologies comprising 100 and 150 nodes. Simulations results are the average of ten seeds that generate different random topologies. The Efficiency represents the average number of packets received at the sink when a battery unit (1mA@) is spent in the whole network and is calculated at the resilience point (data delivery at sinks drops below 50%). Drop Pts are the average number of packets dropped at each node in the entire network at the resilience point. The Re-Txon represents the percentage of data packets that need to be retransmitted due to congestion or node failure problems.

In brief, Pro-SSAS outperforms SSAS and significantly in every performance aspect as can be observed from Table II. The improvements in Pro-SSAS over SSAS+Balancing in percentage are noted in parentheses. Finally, note that the independently proposed proactive hybrid MAC and the balancing routing schemes could be applied jointly. A merged solution will be investigated in future work.

V. CONCLUDING REMARKS

We have proposed a novel fault-tolerant proactive hybrid MAC scheme that efficiently extends the lifetime of energy-vulnerable nodes and more importantly the overall network usability and resilience to failed nodes. The proposed Pro-SSAS scheme integrates TDMA access to vulnerable nodes in contention-based systems. The detection of failure-prone nodes is effectively achieved through a new metric that enables accurate evaluation of how fast the node energy is consumed. Simulation results show significant improvements under a set of performance criteria for WSNs. In particular, the network usability in Pro-SSAS is especially increased compared with a proactive routing alternative.

It is envisioned that cross-layer design combining promising techniques such as hybrid medium access control and proactive failure management schemes would deliver highly energy-efficient communications in WSNs.

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