Design of Noise Measurement Sensor Network: Networking and Communication Part

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***Abstract*—In this paper we report the design and implementation of the networking and communication part of a WSN application for measuring industrial and residential acoustic noise. The network is formed in tree topology and a global synchronization is achieved. A link-state routing is tightly binded with the synchronization so that the network overhead is greatly reduced. Transmission scheduling is implemented in the network due to the fact that noise measuring is time-correlated, resource-consuming, and uninterruptible. The application is built on the *CiNet* cross-layer protocol stack. In our testbed, two IEEE 802.15.4 platforms (Chipcon CC2420 and Jennic JN5148) worked seamlessly. The uniqueness of this application is that it combines routing, global synchronization, and scheduling under a single framework. The network has been already deployed in the residential area of Kokkola city on the western coast of Finland.**

***Keywords*-synchronized network; routing; scheduling; noise measurement; environment monitoring**

I. Introduction

Wireless Sensor Network (WSN) design is usually application oriented [1]. Different applications have different requirements and objectives in protocol design. Though there are plenty of proposals published for WSN, yet a specific application needs a specific solution which is usually an optimization and trade-off between available proposals.

In many countries, environmental acoustic noise is regarded as a critical metric for working and living comfort. Recent studies have shown that if people are exposed to environmental noise levels that are too high, this increases the risks for hearing problems but it also contributes to ischemic heart diseases, hypertension and sleep disorders [2][3]. The European Commission also states that environmental noise negatively affects productivity and that it is one of the major environmental problems in Europe [4].

The traditional way of conducting noise measurements is cumbersome: A technician has to carry a Sound Level Meter (SLM) to a measuring location, set the meter up for a necessary measurement which usually takes several hours and repeat this procedure for all the measuring points. The disadvantages of this method are obvious: 1) a commercial SLM is expensive, making large-scale measurements very costly, 2) point-by-point measurements make the results incoherent timewise, 3) due to the lack of a communication facility, the measured result will not be available in real-time, and 4) SLM needs full attention, which is increasing the work load.

There is a requirement for measuring acoustic noise in both industrial and residential areas in the Ostrobothnia area of Western Finland. In Kokkola city area, officials need a flexible and inexpensive method to monitor environmental noise. Noise sources include loading cargo on a train or a rock concert, among others. Thus the measuring system should be able to cover a large area, such as a university campus, an industrial park, or a residential block. System should be able measure over weekend and store continuous noise levels (1s samples). Real-time data is needed when monitoring rock concert so that officials could react on time. This local need and disadvantages associated with the traditional method gave us the motivation for the design and implementation of a wireless noise sensor network. In such a WSN, a set of wireless sensor nodes are scattered within a concerned area. Each node measures the acoustic noise level at its location, and the measured data is collected by a sink node. Compared with the traditional method, the designed system has the following significant advantages: 1) cost reduction in both sensing devices and workload; 2) real-time, multi-point, coherent measurement; and 3) minimal attention required. The uniqueness of this application is that it combines routing, global synchronization, and scheduling under a single framework. The rest of the paper is arranged as follows: Section II outlines the related work concerning environmental noise monitoring. In section III we illustrate the details of protocol design, including platform selection, protocol stack architecture, timing and synchronization, link-state routing etc.; in section IV the results and corresponding analysis are given; Section V summarizes the design and provides some prospects for future work with this application.

II. Related Work

Transmission of noise sensor measurements in real-time also sets special demands for network protocols. As far as we know, there are only few reports in literature resembling our approach to the problem. This is because wireless noise measurement for WSN is quite special. Thus we review reports and commercial tools related to wireless noise measurement.

The work carried out in [5] is probably the most related one to our project. In that project the Tmote Sky platform was used, and sensors were deployed to measure road traffic noise. From the measured data it is possible to count the number and type of vehicles. The authors assert that large-scale noise measurement using a WSN solution is possible. However, the accuracy of their measurements is not mentioned, and the calibration of nodes was left as an open issue in their work. The sampling rate is set at 8kHz due to the CPU/ADC limit, which does not cover the proper acoustic frequency range.

In [6] the authors stated that wireless sensor network is feasible for the use in environmental noise monitoring. They also evaluated three hardware platforms and two data collection protocols. By using their own custom noise level sensor, demanding noise level calculations could be delegated to dedicated hardware. Their protocol comparison results showed that CTP (Collection Tree Protocol) with LPL (Low Power Listening) provides better performance in terms of energy efficiency compared to CTP and DMAC protocols.

There is a Bluetooth-based solution for noise measurement available in market [7]. In this solution, a Bluetooth piconet which supports a maximum of 5 noise sensor nodes can be deployed. It does not support multi-hop communication, and therefore the application's scale is quite limited.

In SoundEar Pro [8], 10 independent noise level meters can send data wirelessly to the PC within maximum range of 70m. There was no mention about the technology employed in this.

APL Systems Aures [9] is a wireless noise measurement network, which can measure noise levels at multiple points at the same time. The technology behind the product is hidden, but it is told that system works in single a cluster, containing a single network controller and Aures devices.

Compared to reviewed solutions, our system has significant advantages. With multi-hop feature, our wireless noise measurement network is able to cover a large area. Low-cost design makes system much cheaper, decreasing the costs of installation. Because the system uses battery powered sensor nodes with dynamic data routing in network, it is also more flexible than any of the reviewed systems. By choosing suitable duty cycles, the lifetime of the designed battery-powered measurement network can be extended to months.

III. Protocol Design

We only describe the networking and communication function design in this document. The sensing function, hardware design and energy consumption results can be found in [10].

A. Design Objectives

The network is able to support multi-hop tree topology so that a large area can be covered. For example, monitoring environmental noise of surrounding areas of open air rock concert, the network should cover several hundred square meters. In a network size this means that it has 2-3 clusters which each includes 3 to 6 noise sensors. Throughput should be high enough so that the loss of data does not affect the precision of long-term statistics. A global synchronization is necessary in order to produce timely correlated noise data.

The sensors are able to measure the acoustic noise continuously for a long enough period, usually for a whole weekend, and the cost of sensor nodes must be minimized.

The most challenging feature of this application is the collection of large amount of noise data (72 bytes every 5 seconds for every sensor node in network) from the whole network, and delivering that to the sink node in a very short communication window. When a sensor node is measuring the noise, it has to turn off the radio transceiver due to that 1) noise ADC (Analog-to-Digital Conversion) sampling can not be interrupted, 2) radio activities are the source of significant interference to the sampling circuits. This leaves only a short time for all the sensor nodes to send and receive.

Our first design was to let the sensor nodes near the SINK relay data for the remote sensors. Soon we found that it had a severe scaling problem when the number of sensors grows. In order to alleviate the bursty traffic, relay nodes are introduced for the remote sensors. Thus our target WSN contains a SINK node, a set of relay nodes, and a set of noise sensor nodes. The network topology is a multi-hop tree with SINK as the root of the tree. The sensor nodes can be deployed at any arbitrary location in the area concerned. An example application of such a network is shown in Figure 1. The relay nodes take care of relaying sensor packets to the sink.

B. Platform Selection

We choose IEEE 802.15.4 standard [11] compatible modules as our design platform for the following reasons:

1) We had already integrated (microcontroller + RF) modules, with the cross-layer architecture CiNet[12] implemented, which helped reducing the node size and the power consumption as well as the load on software development.
2) IEEE 802.15.4 is the *de facto* standard for WSN. This guarantees the portability and continuity of the project.
3) A sophisticated CSMA/CA MAC protocol eases the design of upper layer protocols.
4) IEEE 802.15.4 offers radio link statistics in terms of Receive Signal Strength Indication (RSSI) or Link

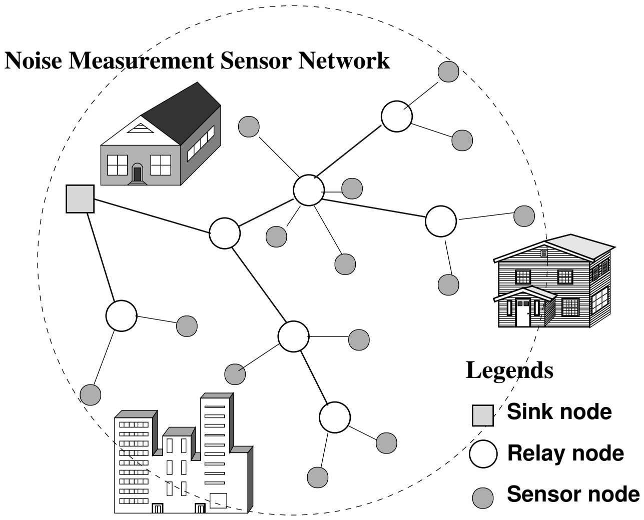


Figure 1. Noise measurement WSN example

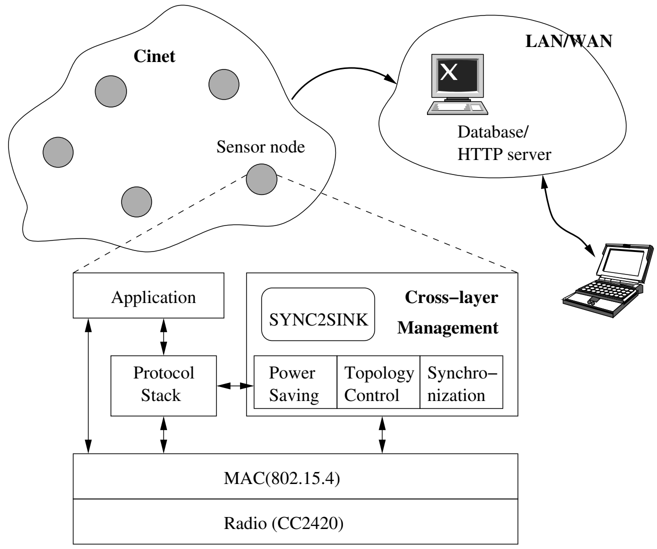


Figure 2. System and node architecture

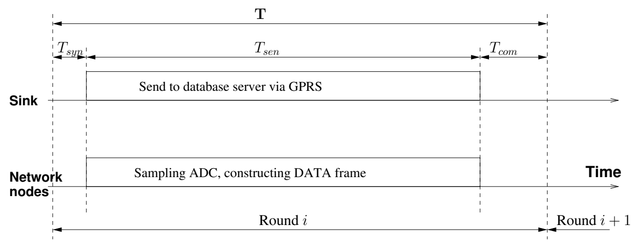


Figure 3. Timeline of the network operations

Quality Indication (LQI). This helps to implement a high throughput link-state routing protocol.

In practice, two platforms are included in our development: one is a microcontroller-RF separated solution (ATmega128+CC2420) and the second is an integrated solution (Jennic JN5148). They work seamlessly in our testbed network.

C. Networking and Synchronization

We developed an integrated synchronization and routing protocol denoted as SYNC2SINK[13] to achieve our objectives. The SYNC2SINK protocol enables the nodes to establish and maintain a route to the sink using the information contained in synchronization frames. SYNC2SINK is built on the CiNet protocol stack[12], which is a cross-layer architecture in which time, radio link state, battery and topology information are shared by sensing, packet transmission and reception, and route table maintenance. The architecture of CiNet can be seen in Figure 2

In the SYNC2SINK protocol a node works periodically in 4 phases: synchronization phase, sensing phase, data communication phase, and optional sleep phase for energy saving. In this particular application the noise measurement has to be done continuously so that the sleep phase is removed. Thus the target network works periodically for synchronization, sensing, and data communications, denoted as $T_{syn}, T_{sen},$ and T_{com} respectively. However, note that during T_{sen} the radio part of the sensor nodes must be turned off due to the uninterruptability of noise sampling and interference reduction. Because the sensed data must be time-stamped, the SINK is synchronized by a server. The sensing phase is started synchronously right after the synchronization phase. The timeline activity of the network is shown in Figure 3.

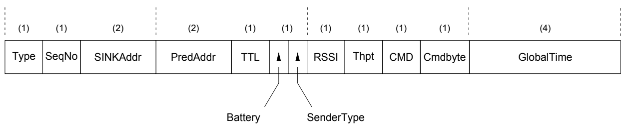
The SINK broadcasts SYNC frames periodically, with the period denoted as $\mathbf{T}$. The frame size is 128 bytes in IEEE 802.15.4 networks. A current data frame can fit maximum of 4.5 second of noise data. Due to that, a 5 seconds sync period is chosen of which sensing phase is 4.5 seconds and 0.5 seconds is transmission phase. The broadcasting of SYNC has four functions: 1) let the whole network become synchronized, 2) let the relay nodes establish a route back to SINK, and 3) let the sensor nodes select the best relay node. The SYNC frame structure is shown in Figure 4(a) it has a length of 16 bytes, and function of its fields is given in Table I. More detailed function of the fields is illustrated in the following section.

Correspondingly, in each synchronization period a sensor node sends a DATA frame back to the SINK. The length of the DATA frame is variable and the structure of DATA frame can be seen in Figure 4(b), in which the *SeqNo* field and *GlobalTime* is copied from the latest SYNC, *SrcAddr* and *PredAddr* are the addresses of the sending node and its predecessor, respectively. This address couple is used by the SINK to figure out the network topology.

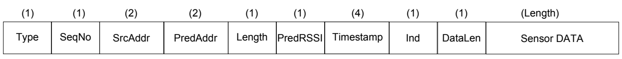
A relay/sensor node must be synchronized by the a SYNC frame, as it is not possible to relay or deliver any data if no

Table I
SYNC FRAME STRUCTURE

Field(octet)	Symbol	Description
Type (1)	—	Indicate that this is a SYNC frame
SeqNo (1)	s_i	Sequence number that increments every cycle
SINKAddr (2)	A_{sink}	Network address of the originating sink node (short IEEE 802.15.4 MAC address)
PredAddr (2)	A_{pred}	the predecessor of the sending node
MaxTTL (1/2)	TTL^*	The upper nibble is the initial value of TTL and kept constant during the broadcasting;
TTL (1/2)	TTL	the lower nibble is set by SINK as TTL^* and decremented by each node, so that the nodes can calculate the hop count to the SINK.
Bat (1/2)	B	The upper nibble, indicating the battery residual of the sending node.
ST(1/2)	—	Indicate the sending node type.
RSSI (1)	Q_{rssi}	Indicate the link quality
Thpt (1)	Ψ	Downlink throughput, basically a statistics of SYNC frame reception rate, can be used to estimate the uplink performance.
Cmd (1)	—	Network command given out by SINK.
CmdData (1)	—	Network command parameter
GlobalTime (4)	T_g	Global time in seconds



(a) SYNC frame structure



(b) DATA frame structure

Figure 4. SYNC and DATA frame structure

route is established. The relay/sensor node must follow a strategy where:

1) When powered up, a node sets the radio module to receive the mode and starts waiting for a SYNC frame for a *SYNC-hunting* time t_{sh} when $t_{sh} \geq \mathbf{T}$.
2) If the SYNC frame is received within t_{sh} time, the node takes the information from the SYNC to the route entry which contains 1) SINKADDR, 2) seqno, 3) predecessor addr, 4) Hop-count to SINK, 5) Link Quality (RSSI); then rebroadcasts the SYNC after the decrementing TTL field. The node is then running in *Synchronized mode*.
3) If no SYNC frame has been received within t_{sh}, the node turns off the radio and sleeps for a random backoff time t_{bk}. When t_{bk} expires, the node goes back to Step 1. Such an operation will prevent the node from spending unnecessary energy in *SYNC-hunting mode*.
4) If the node is in *synchronized mode* and the next m consecutive SYNC frames are missed, the node will turn back to *sync-hunting mode*.

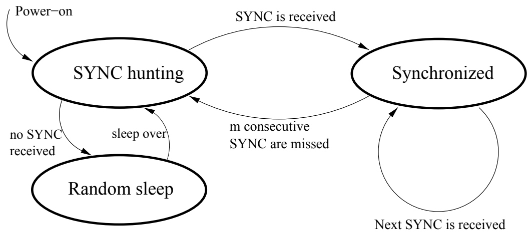


Figure 5. The state-transition diagram of SYNC2SINK

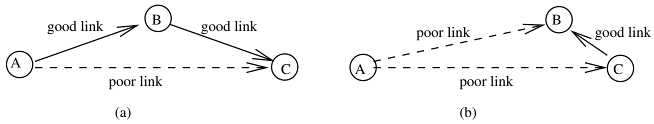


Figure 6. Problem of simple first-SYNC-routing

The state-transition diagram of the nodes is shown in Figure 5.

D. Link-State Routing

In our first design, the relay/sensor nodes establish the route path to the SINK by the taking parameters of the first received SYNC frame (i.e., a greedy algorithm). We found that the DATA frame Packet Receive Ratio (PRR) to SINK was very poor. This is due to the fact that radio links established by the strategy may be poor, because the first arrival SYNC usually comes from a node over the maximum distance. As shown in Figure 6(a), a better choice might be to have a two-hop route from node C to node A, using node B in the middle as a relay, even though C hears SYNC from the A node first.

In order to overcome this problem, we adopt a link-state routing protocol (Power-Aware Routing - PAR[14]). We utilize RSSI, which is a default IEEE802.15.4 MAC layer information. Upon the reception of a SYNC frame, the receiving node can choose a more favourable predecessor as a relay to SINK. According to [15], [16] and a number of related works, an RSSI>-75dBm or equivalently LQI>90 indicates a PRR≥90% over a single link.

The logic of PAR can be depicted as: if a node has received a SYNC frame with new $SeqNo$, it takes the sender of this SYNC as predecessor and mark the RSSI in the route entry; If a node has received a SYNC frame with the same $SeqNo$, it compares the RSSI with the previous one in the route entry. If 1) the new SYNC RSSI is within the range between a lower limit Q_L and a higher limit Q_H, 2) the old one is less than Q_L, 3) the hop count of the new one is no more than the old one plus 2, and 4) the sending node's predecessor is not the receiving node; the receiving node will replace the route entry by the new SYNC's information. If all the SYNC frames that come to this node have RSSI lower than the threshold, the node will simply use the first

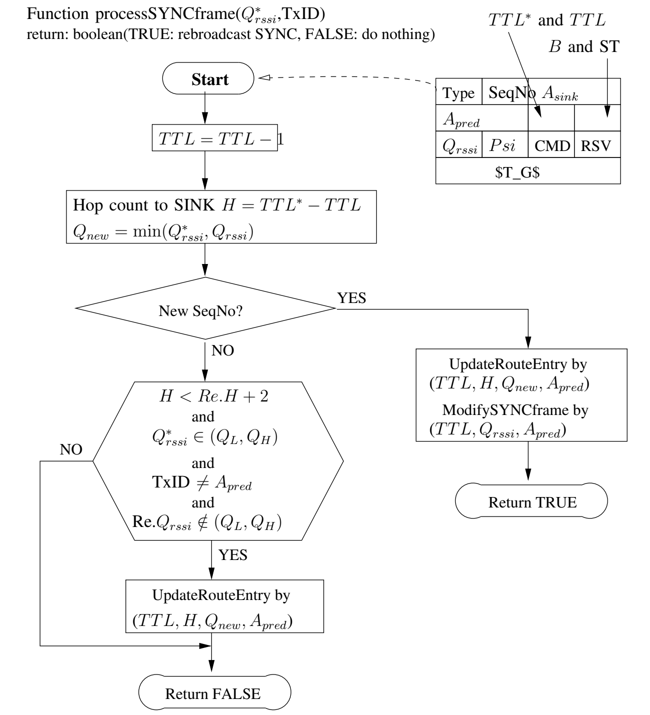


Figure 7. Flowchart of SYNC frame processing ($Re.x$ represent the parameter stored in Route Entry)

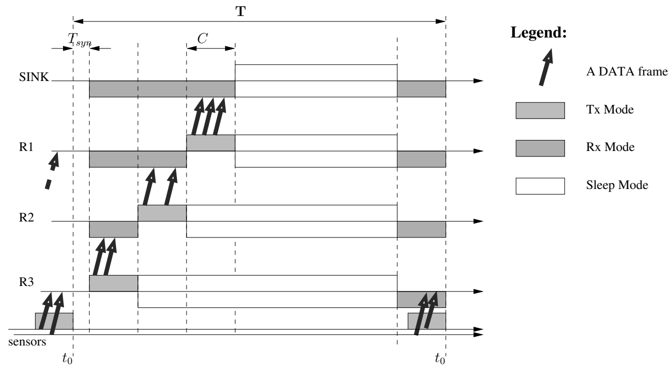


Figure 8. Inter-layer scheduling

one. Here we set a higher limit Q_H in order to prevent too short hops. As an example illustrated in Figure 6(b), both B and C have a poor link to A; however, when B receives a rebroadcast SYNC frame from C with a good RSSI, it shall not replace A by C as its predecessor.

The flowchart about the processing of a SYNC frame is given in Figure 7. The result of adopting the link-state routing can be seen in Section IV.

IV. Results and Analysis

Before setting up a testbed network, important parameters such as T_{com}, T_{syn} must be determined. These parameters are tightly bounded by the hardware properties such as clock oscillator precision, physical and MAC layer features of IEEE 802.15.4 such as CSMA/CA slot time and contention window. As mentioned in Section III, noise sampling must be as continuous as possible —therefore both T_{syn} and T_{com} shall be kept small.

A. SYNC Phase Time T_{syn}

A broadcast frame in IEEE 802.15.4 MAC does not require acknowledgement. According to the analysis in [17], the upper-limit time of broadcasting a SYNC takes

$$\begin{aligned} t_{bc} =& \text{randombackoff}([0, 2^3 - 1] \times 320\mu s) + \\ & \text{dataframeduration}(352\mu s) + \\ & \text{turnroundtime}(192\mu s). \end{aligned}$$

This gives that the maximum $t_{bc} = 2784\mu$s. Thus the phase time for synchronization is

$$T_{syn} = \text{TTL}^* \times t_{bc} \times D \qquad (1)$$

where D is the node density in terms of the node number that can hear each other in a given area.

This analysis does not consider the processing delay in each rebroadcasting node, which is actually a variable due to the task scheduling features of the running operating system. However, the processing of a broadcast message should be set as the highest priority task because this type of messages usually contains network management/control information, thus resulting in very short delay comparing to T_{syn}.

B. Transmission Scheduling

At the end of every cycle, each sensor node generates a DATA frame and sends it out. If we try to deliver all the data frames to the SINK within a small time slot, it will create a burst of radio traffic and PRR can not be optimistic. In order to mitigate the problem, we set up both inter-layer and intra-layer transmission schedules. Here "layer" means the hop count to the SINK.

Inter-layer scheduling is based on hop count to the SINK, denoted as H. Each relay node schedules the radio transceiver into the transmitting mode by

$$t_{tx}(H) = C \cdot (TTL^* - H) + T_0 = C \cdot TTL + T_0 \qquad (2)$$

where C is the scaling constant, and T_0 is the cycle starting time. Figure 8 shows an example. By this scheduling the remote nodes start the forwarding of DATA frames earlier than those closer to the SINK, and data frames are accumulated to the SINK in $C \times TTL^*$ time.

Intra-layer scheduling is done by the order of rebroadcasting SYNC frame. Since a SYNC frame can be heard by all the nodes in radio range, each node marks the sequence of its own broadcasting, and schedules the transmission by

$$t_c(S) = t_{tx}(H) + (S \mod D') \cdot C' \qquad (3)$$

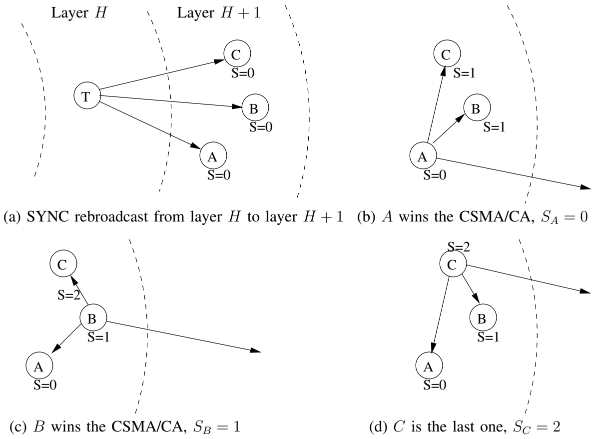


Figure 9. Intra-layer scheduling among nodes A, B, and C

where $t_{tx}(H)$ is obtained from (2), C' is a scaling factor, D' is predefined node density, and S is the sequential number of rebroadcasting SYNC frame in the same layer. An example of determining S is illustrated in Figure 9. A modulus operation bewteen S and D mitigates the scaling problem. However, if the node density is too high in some areas, multiple nodes will get the same t_c and in this case they will rely on IEEE802.15.4 CSMA/CA to avoid collisions.

C. Server-Sink Synchronization

The SINK acts simply as a passthrough gateway between the WSN and a webserver which manages the sensor data in the SQL database. Therefore the measurement must follow the server time so that sensor data can be correctly stored and displayed. The connection between the server and the sink is either a direct RS-232 link or a GPRS channel. In order to synchronize with the server time, a fine adjustment is implemented between the SINK and the server as illustrated in the follow.

Right after a SYNC frame has been sent out, the SINK immediately sends a polling message to the server. After the reception of the polling message, the server records the time when the message arrives, and compares it with the time of the previous arrival, denoted as $\delta_i = t_{i+1} - t_i - \mathbf{T}$, and immeadiately sends δ_i in a reply message, as shown in Figure 10. The SINK adjusts its next SYNC broadcasting time by $T_{i+1} = T_i + \mathbf{T} + \delta_i$. This adjustment will force the SYNC broadcasting to follow the server time.

This simple time adjustment worked fine in our testbed. We tested the algorithm for nearly 1 day and the synchronization was maintained well (with mean δ only 0.0767ms).

D. Test Settings

We designed 5 scenarios to test different aspects of our communication protocol. In the first scenario, we examined our synchronization performance. In the second scenario, we tested the link-state routing performance by varying

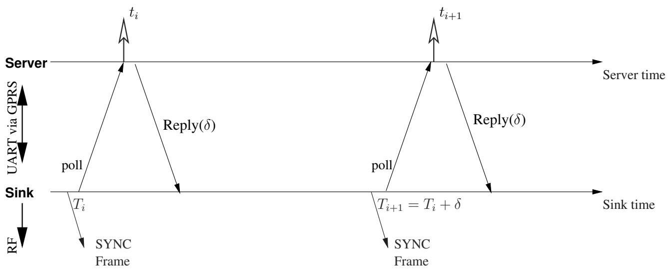


Figure 10. Time Adjustment between Server PC and the SINK

Table II
TESTBED NETWORK SETTINGS

Cycle time $\mathbf{T}$	5 sec.
Data frames k per cycle	1
Data frame length	80 bytes
T_{com}, T_{sen}	1/4 sec.
Node time precision	0.001 sec.
Inter-layer Delay Constant C	0.15 sec.
Run time of each senario	7200 sec. or over night
Q_H (LQI)	150
Q_L (LQI)	varying

the LQI threshold, to obtain an optimal LQI threshold. In the third scenario, single-hop capacity was tested. The last two scenarios were designed to verify dynamic routing and multi-hop communication performance, respectively. More detailed protocol parameter settings are given in Table II for all the scenarios.

We first put five noise sensor nodes in a coffee room to exam the synchronization performance. Figure 11 shows the time-line of the measurement results, and it can be seen that they are time-correlated.

Then we set up a test network which has nine relay nodes

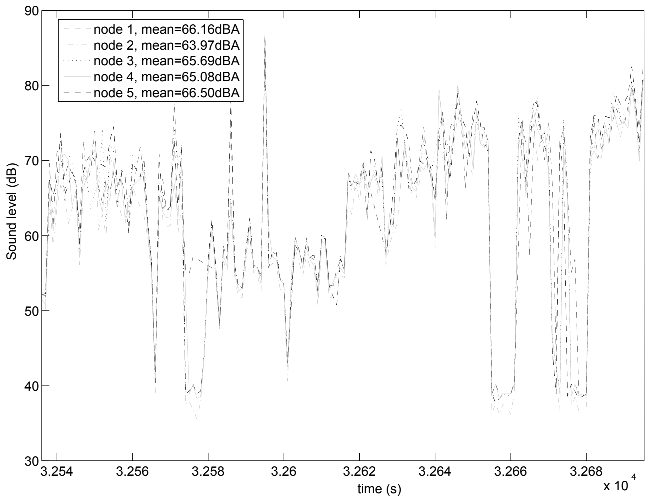


Figure 11. Measurement result of 5 nodes in a coffee room

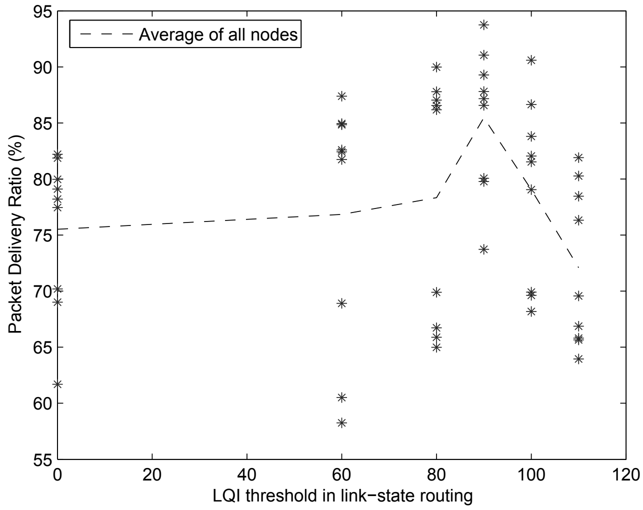


Figure 12. Packet receive ratio at different LQI settings in Link-state routing

and one SINK at 4th floor of our laboratory building. In each cycle, a relay node produces one data frame and sends it back to the SINK.

Figure 12 shows the link-state routing performance with different LQI thresholds. Note that LQI_{th}=0 (or RSSI=-128dBm) indicates a non-Link-State routing protocol. It can be seen that at LQI_{th}=90 (or RSSI=-75dBm) the PRR hits the maximum value in the multi-hop scenario, which improves PRR by 10% compared with that of LQI_{th}=0. A low LQI threshold results in that the network has smaller number of hops from the sink to the most remote nodes, but the radio link goodput is poor due to the long distance of the hops. On the other hand, a high LQI threshold gives a good radio link performance, but a remote data packet has to be relayed by more nodes back to the SINK, and it also aggravates the hidden node problem [18].

The third test was for single-hop capacity. We set up a number of sensor nodes as the first layer from a SINK. It can be seen that using intra-layer scheduling, one SINK can serve up to 14 sensor nodes with an average PRR greater than 96%. Table III shows the results of setting 12, 13, and 14 nodes respectively.

Table III
SINGLE-HOP PACKET DELIVERY PERFORMANCE

Node No.	PRR_{min}	PRR_{max}	Mean
12	0.9870	0.9978	0.9916
13	0.9739	0.9942	0.9868
14	0.9301	0.9892	0.9659

Our next scenario was a two-hop setup with 1 relay and 16 sensors. This setup was meant to exam the dynamic routing performance. The result given in Figure 13 shows how well the dynamic link-state routing performs. The second column

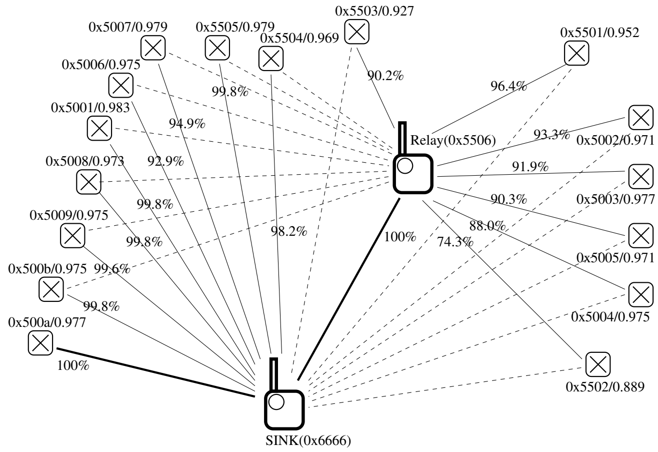


Figure 13. The 2-hop scenario setup and results. A solid line means that the link is used primarily. A dotted link means the link is occasionally used. The number associated to node is the node address.

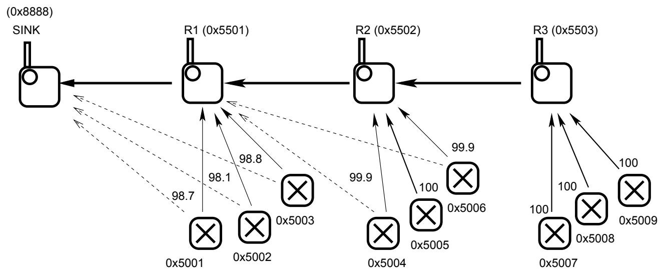


Figure 14. The 4-hop scenario setup and link usages. A solid line means that link is used primarily (usage in %). A dotted line means the link is occasionally used. The number associated to node is the node address.

of Table IV shows the PRR results. A node mostly sends data to its closest SINK/relay, and in case of link fluctuation, almost all of them have tried the alternative route.

The last scenario was a 4-hop setup with 3 relays and 9 sensors. This setup was meant to exam the scalablity of routing protocol. The setup scenario is shown in Figure 14. PRR results are in the third column of Table IV. Results are good and it shows that scheduling works.

V. CONCLUSION

In this paper we report the design and implementation of a protocol suite for a WSN application which measures the instantaneous environmental acoustic noise in a given area. The protocol features synchronization, link-state routing, and can be deployed/retrieved quickly. A good packet delivery ratio is achieved by carefully adjusting the timing and link-state parameters. The most significant unique feature of our design is the support of multi-hop communications, which makes large-scale noise measurement possible. This feature has not been seen in any peer solution.

Table IV
2-HOP AND 4-HOP LINK-STATE PERFORMANCE

Node addr	PRR 2-hop	PRR 4-hop
5506	0.957	-
5501	-	0.984
5502	-	0.969
5503	-	0.957
5001	0.983	0.978
5002	0.971	0.975
5003	0.977	0.977
5004	0.975	0.966
5005	0.971	0.967
5006	0.975	0.965
5007	0.979	0.947
5008	0.973	0.956
5009	0.975	0.956
500a	0.977	-
500b	0.975	-
5501	0.952	-
5502	0.889	-
5503	0.927	-
5504	0.969	-
5505	0.979	-

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