Sampling and Transport Co-design in Wireless Sensor Networks

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***Abstract*—A key task in Wireless Sensor Networks (WSNs) is to deliver specific information about a spatial phenomenon of interest. To this end, a few Sensor Nodes (SNs) sample the phenomenon and transmit the acquired samples, typically multihop, to the application through a gateway called sink. Many applications require the spatial sampling to be accurate and the delivery to be reliable. However, providing a higher accuracy/reliability comes at the cost of higher energy overhead as additional messages are required: increasing the number of samples to increase the accuracy of sampling and increasing the number of retransmissions to increase the transport reliability. Existing design approaches overlook optimized spatial sampling accuracy and transport reliability in combination for minimizing energy consumption. In this paper, we sketch a new approach in providing the optimized solution for sampling accuracy and transport reliability in composition for a maximized efficiency.**

***Keywords*-Wireless Sensor Networks, Sampling, Transport, Optimization, Information Quality**

I. INTRODUCTION

In Wireless Sensor Networks (WSNs) delivering the gathered information with the user required quality is the main concern. To satisfy the user required quality, we should carefully design the functional blocks, such as (a) sampling schemes in order to accurately represent the physical phenomena, and (b) the transport schemes in order to reliably deliver the information to the sink. In our work, we focus on the key operations of spatial sampling and transport and their quality attributes, i.e., accuracy and reliability, respectively.

A higher accuracy of spatial sampling is usually achieved through a higher number of sampling sensor nodes(SNs) in the area of the physical phenomenon resulting in a higher energy/bandwidth overhead. However, the sampling accuracy satisfies user requirements assuming the information transport to be perfect, which is not true in WSNs. On the other hand, transport reliability usually achieved through a higher number of retransmissions assume the sampling block to be perfect while satisfying user requirements.

Usually in WSNs the end user/application/controller will have a particular requirement of user required sensing accuracy. The sampling accuracy generated at some former time in the network differs from the user required accuracy while transporting the information towards sink, until and unless assuming perfect transport reliability. Generally, reliability is tunable by number of transmissions and redundant information, i.e., sending multiple instances of the same information. Moreover, the application reliability experienced at the sink should be always satisfying the user required reliability.

The user/application view considering the spatial phenomena of interest requires a certain sensing accuracy (e.g., perimeter of a hole in the phenomena [6], spatial distribution of the phenomena [3]). Considering the design view, the sampling accuracy can be tuned by injecting some redundancy (e.g., activating more SNs on the border of the coverage hole) and protocols such as [3] allow for over-sampling. On the other hand, transporting the samples from the spatial phenomena of interest with a certain designed reliability requires a co-design of sampling and information transport with certain sampling accuracy, transport reliability, best effort timeliness and maximizing efficiency. In this order, the sensing accuracy is the co-design of spatial sampling accuracy and transport reliability. Hence, in our work for a given sensing accuracy, we provide the roadmap for the optimal solution with online adaptation by maximizing energy efficiency.

The state-of-the-art on Quality of Information (QoI) [8][5]and Quality of Service (QoS) [1][4] in WSN lacks the online composite adaptation of sampling accuracy and transport reliability to the network conditions and application requirements. In fact, available approaches usually target single functional blocks [2][3], assuming that other functional blocks are perfect. The performed sampling accuracy satisfies the application requirements only if the information transport is perfect, which is not true in WSNs. On the other hand, the transport reliability assumes the sampling block to be perfect while addressing the application requirements. The optimized co-design of sampling and transport that maximizes the energy efficiency while satisfying the requirements is lacking in available approaches. In particular, there are no efforts in WSNs addressing the composite tunability of sampling accuracy and transport reliability.

Achieving both sampling accuracy and transport reliability while maximizing efficiency requires a sophisticated tradeoff technique, which is the main objective of this work. In this paper, we discuss the challenges to develop the required algorithms to provide such technique for generalized WSNs. Then, we present our methodology and a brief overview of our planned research.

II. SAMPLING AND TRANSPORT CO-DESIGN

Before sketching our approach to provide sampling and transport co-design, we briefly discuss the main challenges

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that we face.

A. Key Research Challenges

We consider a physical phenomenon of interest that spans a specific small sub area of the WSN field. In general, the application is interested in one specific information about this spatial phenomenon, e.g., the perimeter of its area. We consider the communication disruptions constitute the most frequent failures. Collisions, contention and congestion constitute the major causes of message loss and hinder information transport in WSNs. We assume that network conditions are dynamic and application requirements are evolvable. We assume that the most strict application requirements do not exceed the maximal capacity of the WSN [7].

A minimum number of spatial samples S_{min} is required to reconstruct the information on the sink. To this end, S_{tx} SNs sample this spatial phenomenon and transmit the samples towards the sink. The hops are considered as the average hop count from all the active sources to the sink. On the other hand, as we are interested in the small sub area of the phenomenon, variations of 1 or 2 hops do not affect the model and the end result. This is the case if the phenomenon area is small compared to the WSN field which is often the case for event-driven applications. The application requirements can be distributed to the SNs via a standard dissemination mechanism. We consider that the number of sampling SNs S_{tx} can be controlled, e.g., through an existing duty cycling algorithm that interacts with the sampling scheme, e.g., [3] to decide on which nodes to keep active.

Increasing or decreasing the number of SNs to send a sample will increase, respectively, decrease the sensing accuracy. While it would be possible to satisfy the requirement by sending exactly S_{min} samples, this is no optimal solution in terms of energy efficiency. Hence, we consider packet transmission are the most expensive atomic operations in WSNs. Accordingly, we abstract energy efficiency in terms of number of retransmissions. Distributing the requirement to multiple paths the requirement (S_{rx} in Fig. 1) is achievable with fewer retransmissions needed even though more hops are included as show in Fig. 1. As we consider the spatial phenomena of interest, we intend to send S_{min} samples as the primary samples regardless of which SNs in the phenomena area will send the samples. Reliability can be seen as a hidden requirement, derived from the accuracy requirement.

B. The Roadmap towards the Co-design

Providing a specific requirement of S_{min} samples, the application actually expects exactly $S_{rx} = S_{min}$ samples to be delivered. However, this guarantee is hard to be satisfied in WSNs. Therefore, we assume the application requires to meet the requirements with certain fidelity $Fi_{acc} \in [0, 1]$. Furthermore, generating only S_{min} samples and delivering all of them to the sink would require a large number of retransmissions.

Preliminary investigations have shown that by slightly increasing the number of generated samples S_{tx}. We can significantly reduce the total number of transmissions needed to deliver S_{min} samples to the application. However, sending too many additional samples will finally result in unnecessary high number of retransmissions. Hence, we aim to find the optimal number of additional samples and the optimal path reliability that result in a minimal number of total retransmissions. Such an optimization allows to co-design sampling and transport for a maximized message efficiency, which transforms into maximized energy efficiency, as usually radio is the most energy consuming module on a SN. The ultimate goal is to use the results of the optimization to develop an integrated sampling and transport algorithm.

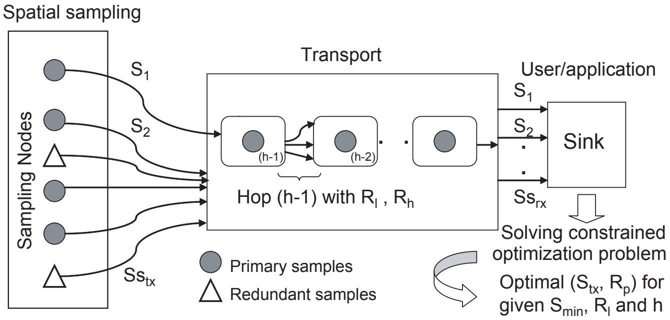

Fig. 1: A holistic view of sampling transport, and application interactions.

The main objective is to supply the sink with exactly the number of samples required. Due to the probabilistic characteristics of WSNs no guarantee can be given, but only that the required number of samples arrive at the sink at least with high probability. Fig. 1 illustrates the two operations spatial sampling and transport. For readability, we emphasize one sample (S_1) and one path towards the sink. The main reasoning behind the targeted sampling and transport co-design is to online tune both operations using optimized S_{tx} and R_p values. To this end, firstly, we aim to solve the optimization problem. This requires to analytically express the total number of retransmissions $\#ret_{total}$ as a function of the sampling accuracy S_{min} and transport reliability R_p and to select those pairs that globally minimize the $\#ret_{total}$.

C. On Practical Issues of Sampling and Transport Co-design

Based on the design goal, the objective function is to satisfy the user requirement based on the number of samples and reliability. In practicality issue of sampling and transport co-design, we consider that the function of optimal solution will be running on a powerful sink with sustained processing power. As the basic step, the sink solves the optimization problem constrained by the reliability constraint R_{GDT} and then disseminates the required optimal S_{min} towards the sources. The optimized values known by the SNs, pertains to satisfy the user requirements obtained from the sink. There are some existing algorithms such as [3], which can be applied to reduce the mean square error of the achieved measurement of raw sampling accuracy and allowing over-sampling.

Algorithm 1 The Design of Integrated Sampling and Transport

```
Const: $h$, $R_l$, $S_{min}$
Var: $f_1$, $f_2$, $S_{tx}$, $R_p$
————————————————————
/*Sampling SN $\rightarrow$ Tunable Sampling with $S_{tx}$:*/
if $SN_i$ in phenomenon area then
    $S_{min}$ = Sample();
    $S_{tx}$ = $f_1(h, S_{min}, R_l)$;
    execute Sample($S_{tx}$);
    if $SN_i$ is a sampling node then
        take a sample $S_i$;
        $R_h$ = $f_2(h, S_{min}, R_l)$;
        transport($S_i$, $R_h$);
        Exit();
    end if
end if
————————————————————
/*Transport SN $\rightarrow$ Tunable Transport with $R_h$:*/
UPON reception of msg (sample, $R_h$):
transport(sample, $R_h$);
{
    $\#ret_h = \frac{log(1-R_h)}{log(1-R_l)}$
    Transmit msg (sample, $R_h$) $\#ret_h$+1 provided an implicit ACK is not received
    Exit();
}
```

As show in Fig. 2, the sampling scheme is informed with two functions f_1 and f_2 after receiving the application requirements from the sink. The sampling algorithm can self adapt to provide the S_{tx} and R_h. However, to calculate the optimal tuple of providing the required samples S_{min}, we need to solve the optimal constrained problem.

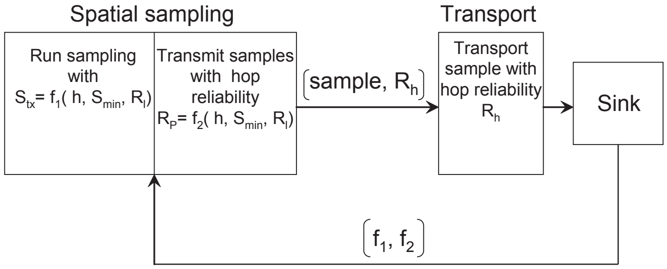

Fig. 2: Basic message flow in integrated sampling and transport.

III. CONCLUSION

Through this paper, we have briefed on how we plan to achieve the co-design of sampling and transport as per the application requirements. We plan to introduce the analytical model for the case that no differences between sensor readings have to be regarded. The on going optimized solution depending on the application requirements, reduces the total number of retransmissions by adding redundancy and sending more samples than required.

In our ongoing work we aim to provide:

- A mathematical model with composition of sampling accuracy and transport reliability, based on the probabilistic behavior of WSNs.
- To formulate and solve a constrained optimization problem to determine the optimal combination of sampling accuracy and transport reliability that maximizes efficiency.
- The integrated sampling and transport algorithm that satisfies evolving requirements on accuracy and reliability.
- Compare and prove the analytical work with extensive simulations.

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