Exploiting Spatio-Temporal Correlation for Reliable Information Transport in WSNs

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ABSTRACT

Delivering reliable services in service oriented architectures entails the underlying basis of having communication network models and well structured systems. With the rapid proliferation of ad-hoc mode of communication the reliable delivery of services increasingly encounter new communication and network perturbations. Empirically the core of service delivery in WSNs (Wireless Sensor Networks) is information transport from the sensor nodes to the sink node where the service resides. In this work we provide a reliable information transport for enhanced service delivery by using spatio-temporal correlation in WSN. The classification for different types of information required by the services is also presented. To overcome dynamic network conditions and evolving service requirements an adaptive retransmission mechanism based on spatial correlation is utilized. Simulation results show that the proposed solutions provide service specific reliability and save expensive retransmissions and thus provide energy efficient solution.

Key Words: **Wireless Sensor Networks, Service Availability, Reliable Information Transport, Tunable Reliability, Spatial Redundancy.**

1. INTRODUCTION

The services in service oriented architectures are implicitly associated with well structured environments. However, in wireless adhoc environments the basis behind assured service delivery requires reliable information transport. WSN comprise a growing research area in ad-hoc networking. WSN cover a wide variety of devices, communication systems and provide a diverse set of services. Typical WSN services involve tracking, monitoring and reporting events to the users. Furthermore, with the rapid emergence of WSN services, they are becoming integral part of ubiquitous and pervasive systems, grid systems (Sensor Grid [1-2]) and web services (Sensor Web [3-4]). The different WSNs work in collaboration to provide services to the users as shown in Fig. 1. The users require a service from WSNs along with a set of requirements on the reliability. In response, WSNs collect and transport information for the required service from different parts of the network. Thus,

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"information transport" is at the core of any service which builds on the information from WSNs via a gateway node sink. This work targets the information transport paradigm to ensure the availability of a service and thus hinder in achieving desired reliability. Pragmatically, it is hard to control the changing network conditions. Therefore, the protocols need to be adapted according to changing conditions. This leads to the problem of establishing which protocol parameters to tune such that the desired level of service reliability is achieved despite failures. The existing approaches utilize either temporal correlation, (e.g. retransmissions [5]) or spatial correlation, (e.g. number of sources [6] or paths [7]) or some combinations of them [8] to some extent overcome failures without considering variable service reliability requirements. Normally, WSNs utilize intrinsic sensor node redundancy for assuring the desired information delivery reliability. However, the redundancy of sensor nodes comes at the cost as the delivery of redundant information also depletes the limited node energy. Furthermore, different services running on WSNs demand various types of information with diverse reliability requirements. Varying service requirements impose consequent reliability obligations for the information transport in a WSN. In addition, the same WSN service may change its requirements over time. The existing solutions generally assume certain reliability requirements and network conditions and there exist only focused solutions. To the best of our knowledge, there exists no representative solution which copes with both evolving service requirements on reliability and dynamic network conditions.

On this background the paper makes the following contributions.

The spatio-temporal correlations of interest for information transport are identified and tuned in such a way that service requirements are always fulfilled.

We develop an adaptable reliable information transport approach that relies on existing approaches for ensuring the availability of service despite evolving service requirements and network conditions.

We show how the availability of services is maintained in the presence of perturbations by efficiently collecting network health indicators and by exploiting spatio-temporal correlations.

We classify and develop algorithms for reliable delivery of different types of information.

The rest of the paper is organized as follows. Section 2 details the system, perturbation and reliability models relevant to WSN, followed by the related work in Section

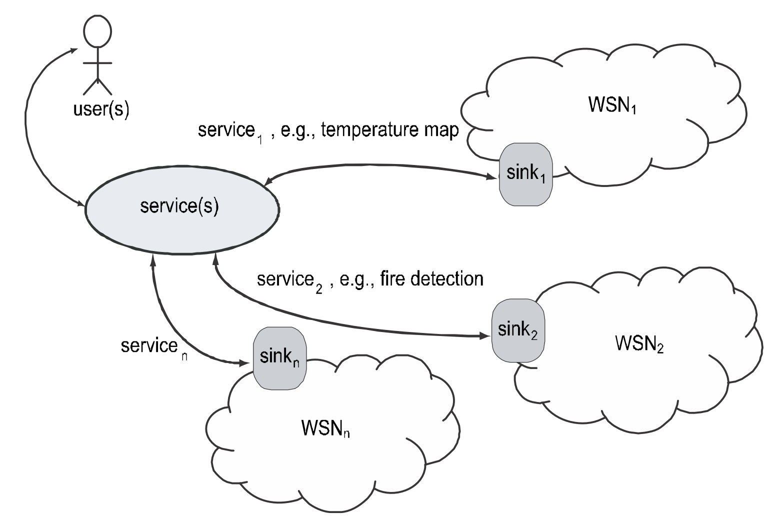


FIG. 1. GENERIC WSN SERVICE MODEL

3. The problem statement is presented in Section 4. Section 5 presents the proposed solutions to ensure the availability of a service. We evaluate the proposed approaches using simulations in Section 6. The conclusion and future work appear in Section 7.

2. MODELS AND CLASSIFICATION

First, a comprehensive system and perturbation model is presented. Next, the information transport reliability requirements are elaborated.

2.1 System Model

We consider a WSN where N [0..N-1] sensor nodes are deployed with single sink. Typically, a sensor node is equipped with one or more sensors, short range radios for communication, less processing, memory and energy capabilities compared to the sink, which is adequate in resources. All sensor nodes including sink are static in nature. Sensor nodes communicate via bi-directional links employing CSMA (Carrier Sense Multiple Access) based MAC (Medium Access Control) protocol. For any two nodes X, Y the link quality is defined as $LQ=p_{(X;Y)}:p_{(Y;X)}$, where $p_{(X;Y)}$ and $p_{(Y;X)}$ indicates message reception probability. X,Y are defined to be neighbors, if $LQ \neq 0$ showing that IACK (Implicit Acknowledgements) can be used in our model. The sequence of hops (X,h_1), $(h_1,h_2)...(h_f,0)$ is a path, $Path_i$, from Node X to the sink. An underlying routing protocol is considered which provides a next hop along the $Path_i$.

2.2 Perturbation Model

Service availability effectively requires the identification of the relevant node and communication perturbations. The temporal evolvability of these perturbations is mainly emphasized, which hinders in maintaining the required level of service reliability. Inexpensive hardware, less resources and harsh environmental conditions lead to frequent failures in WSN [9]. The failure classification is carried out with respect to message loss due to both node and communication failures.

(1) *Communication Level Failures:* Communication disruptions constitute the most frequent failure in WSN. High bit error rate of wireless links, collisions and contention are the major causes of the message loss.

(2) *Node Level Failures:* At node level message loss is caused by crashed behavior of sensor nodes due to energy depletion.

This may impact the number of sources reporting an event. In this work, intentional failures such as Byzantine or intrusions are not considered. For sink, as it plays central role, we assume that backups are present and thus no failure occurs.

2.3 Reliability Model

Different services require different types of information from WSNs. Due to the increasing number of services, we propose an abstraction for services corresponding to the information they expect from the WSN. Such an abstraction supports service independence and transparency for the information transport. We refer to an information area as the geographic area where raw data is generated and the information of interest is extracted through in-network processing as depicted in Fig. 2. An established example of information area is the event area. An information entity is the processed raw data which is required by the service. In an information area, nodes are classified as the data and information nodes. The data nodes generate raw data while information nodes generate information entities. It is assumed that the information entity is realized through a single message. An information entity is required to be transported to the sink via relay nodes. The information entity can be generated on a single node (e.g. cluster head, fusion center, aggregation node etc.) or in a distributed manner by multiple nodes (spatially correlated). The information entities can also be grouped for higher semantics, e.g., the event perimeter.

Accordingly, we classify any information required by the services into two broader classes: Atomic information and Composite information. The atomic information is composed of a single information entity (Fig. 2(a)), which cannot be sub-divided and is complete in nature, e.g., aggregated value of many sensor nodes. Alternately, composite information is composed of a set of unique information entities from different information nodes (Fig. 2(b)). For example, the tracking or event perimeter services focus on boundaries of the object/event to better understand its progression. These boundaries can have different shapes/sizes. The service can reconstruct the boundaries to track an object if they have sufficient information entities, i.e. boundary samples. The service reliability requirements are typically statistical in nature. For example, monitoring services do not require reliability of a single information entity but require a prescribed number of entities to be available. Similarly, event detection services require that a certain number of events to be reported over the lifetime of WSNs. This entails providing x% (probabilisticallyguaranteed) reliable information transport instead of the best effort or transporting all information entities. Accordingly, the service level end-to-end reliability for information transport $R_d (0<R_d<1)$ is described by the probability of successfully transporting the information entity to the sink. Based on the service requirements, the atomic information transport reliability is defined as a degree of tolerating the information loss over time. For composite information, transport reliability is defined as the degree of tolerating loss of information entities by a service.

3. RELATED WORK

In [10], authors have proposed a hop-by-hop technique for the information transport. In order to assure reliability, the sequence of packets is sent to the next hop with EACK (Explicit Acknowledgement). The proposed solution differs in considering spatial redundancy along with retransmissions. Our work also exploits the broadcast nature of WSN and utilizes IACK which reduces the overhead of explicitly sending an acknowledgement.

RMST (Reliable Multi-Segment Transport) [5] jointly uses selective negative ACK and timer-driven mechanisms for loss detection and notification. It places responsibility for message loss detection at the receivers (which can be intermediate nodes as well as the sink). RMST also does not exploit the spatial redundancy inside the network and propose retransmissions at the MAC and transport layers. Similarly, ART (Asymmetric Reliable Transport) [11] utilizes timer driven retransmissions between the essential nodes and the source nodes and does not explicitly consider spatial redundancy. Service level reliability is not available in these approaches.

In [6], the authors present ESRT (Event to Sink Reliable Transport) protocol that achieves reliability by adjusting the reporting rate of the sensor nodes depending upon

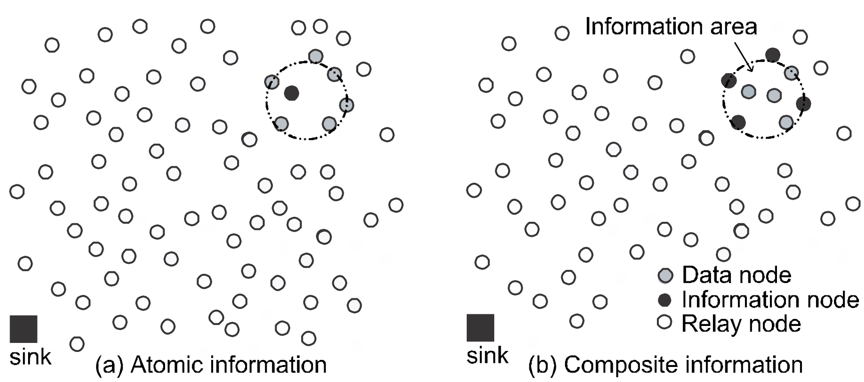


FIG. 2. INFORMATION CLASSIFICATION

the current network load. ESRT is developed for continuous event services, where an adaptation of the data report rate makes the sense. Our work provides reliability at the hop level whereas ESRT provides end to end reliability which is difficult to maintain in WSN. DTSN (Distributed Transport for Sensor Networks) [16] and STCP (Sensor Transmission Control Protocol) [12] provide differentiated reliability using end-to-end retransmissions. DTSN besides retransmission uses FEC (Forward Error Codes) to enhance reliability. The end-to-end retransmissions do not respond quickly in face of perturbations thus hop-by-hop retransmission strategy is adopted. On the other hand FEC requires a high level of computation thus limiting its practicality for WSNs.

4. PROBLEM STATEMENT

In [8] the authors provide a reliable information transport protocol termed as RBC (Reliable Bursty Convergcast). However, RBC lacks in adaptation according to service requirements and evolving network conditions. Since, RBC implements a suite of reliability mechanisms we aim at adapting RBC for different service requirements and for different network conditions. The RBC protocol provides reliability through hop-by-hop retransmission-based loss recovery. It uses windowless block ACK and IACK along with the fixed number of retransmissions to deal with the failures. RBC implicitly assume that more than one sensor nodes are sending the information towards the sink. It should be noted that the RBC always try to provide the high reliability. A comprehensive performance analysis of RBC can be found in [8,14].

4.1 Non-Adaptiveness of RBC

For motivation let us consider a scenario where service requires reliable transportation of atomic information. In the considered situation the atomic information is generated by many sensor nodes. To this end, 4 sensor nodes are assumed for sending the redundant information. We investigate the RBC¡¯s capability to adapt to dynamic network conditions and to maintain the varying reliability requirements. This is crucial for availability of service since the network conditions may change during the lifetime of the service. For link quality indicator, the wireless channel BEP (Bit Error Probability) is considered which varies the link reliability between the sensor nodes. To represent different link quality the BEP is varied from 0- 0:02.

We performed simulations for 25 nodes with the simulation settings as described in Section 5. Fig. 3 shows the RBC¡¯s adaptation for varying reliability requirements and changing network conditions. For BEP between 0:0 and 0:01 RBC over performs by providing high reliability

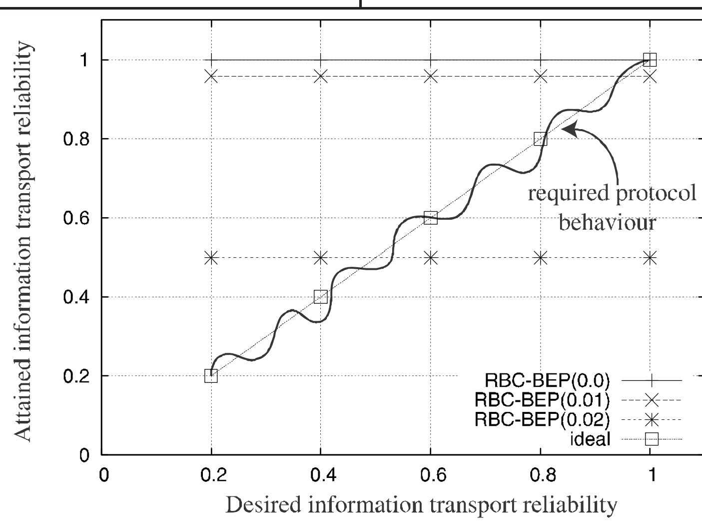


FIG. 3. NON-ADAPTIVE BEHAVIOR OF RBC

compared to the service requirements. This shows RBC¡¯s lack of adaptation for different service reliability requirements and requires that the information delivery approaches must be aware of service requirements. As BEP increases the RBC reliability decreases suggesting that the RBC performs poor in bad network conditions and thus do not adapt well. Although RBC includes a fixed number of maximum retransmissions, i.e. 2, but it is not sufficient to cope with the evolving network conditions. In general, RBC provides a constant reliability for a given network condition and thus does not adapt to varying service requirements which can be either higher or lower than the achieved reliability. This motivates for an adaptive protocol which provides service specific reliability and adapt to network conditions in appropriate way such that it follows the ideal case as shown in Fig. 3.

4.2 Spatio-Temporal Classification

We identify different spatio-temporal parameters for the availability of the service such as number of sources (#src), maximum number of retransmissions (#ret) and number of cache points (#CP). #CP corresponds to storing the messages along the path to recover message loss. In [15] it is shown that storing message at each hop outperforms other approaches in terms of reliability. Accordingly, the information is cached at each hop along the path until an ACK is received.

To monitor the network conditions different indicators can be utilized, e.g., BEP, SNR (Signal to Noise Ratio), RSSI (Received Signal Strength Indicator), LQI (Link Quality Indicator), PER (Packet Error Rate) and path estimators (ETX [16], GEM [17]). RSSI is not an efficient indicator of link quality [18] and LQI is specific to some radios. ETX and GEM on the other hand provide path quality and can be misleading due to evolving network conditions. In this work, BEP is considered as a generic link quality indicator. BEP reflects wide range of cases, i.e., network congestion, collisions and contention.

5. SPATIO-TEMPORAL CORRELATION FOR RELIABLE INFORMATION TRANSPORT

We now develop our approach AReIT (Adaptive Reliable Information Transport) that allows exploiting spatio-temporal correlation to provide reliable service delivery. We focus on how to integrate and tune #src and #ret to fulfill the service reliability requirements in the face of failures. In this section first the requirements and assumptions driving our approach are described. Next, the analytical model for the information transport is developed followed by spatio-temporal adaptation for atomic and composite information.

5.1 Requirements and Assumptions

We identify the following requirements on the proposed solutions. First, the primary objective is to achieve end-to-end reliability for transporting information entities generated by the information nodes to a sink. Second, the solution should be energy efficient. Generally, energy efficiency is a primary concern rather than the latency in many WSN services. Therefore, for long-term unattended operation of the network, the information transport should minimize energy consumption by reducing number of transmissions. Furthermore, the proposed approaches make following three assumptions about the underlying network. First, we assumes that the information rate is low such that network congestion is negligible. This is a reasonable assumption for most of the services [19-21]. Second, the snooping of messages comes at low cost. Therefore, a LPL (Low Power Listening) mechanism [22] can be used resulting in low cost snooping [18]. In future we will investigate the performance of our approaches with different LPL mechanisms. Third, low contention inside the network is assumed. However, for low information rates, the transmission collisions are negligible which leads to low contention.

Sensor node selects itself as information node based on service requirements and type of information. Sensor nodes locally identify the type of generated information based on criteria specified by the service, e.g., a clustering algorithm selects the cluster head for the data collection to generate the atomic information. Such criteria specification is beyond the scope of this paper and we assume that the type of information is specified by the service during design/deployment time.

5.2 Analytical Model for Information Transport Reliability

Let us consider a Node X transporting information via Node Y along $Path_i$, h hops away from the sink. The transport reliability from Node X to the sink is:

$$R_d = \prod_h R_{hop} \quad (1)$$

where R_{hop} is the hop reliability. To ensure reliability across a hop (X;Y) and to cope with failures, i.e. message loss, retransmissions are carried. Let r be the number of transmissions than information transport reliability across a hop (X;Y) is:

$$R_{hop} = 1- (1-p_{(X;Y)}p_{(Y;X)})^r = 1-(1-LQ)^r \quad (2)$$

Since r is the total number of transmissions, #ret will be r-1.

For many WSN services more than one sensor node generate messages such as event reporting services. Consequently, the information from source nodes normally have spatial correlation. Accordingly, the integrated reliability across a hop will be:

$$R = 1 - (1-R_{hop})^s \quad (3)$$

where s = #src transporting the information to the sink. Equating Equations (2-3) yields:

$$R = 1 - ((1 - LQ)^r)^s \quad (4)$$

Equation (4) utilizes a spatio-temporal mechanism which explicitly accounts for the spatial redundancy in the form of #src and the temporal redundancy in the form of #ret.

5.3 Adaptation for Atomic Information

Our solution adapts spatio-temporal correlation to overcome failures. Algorithm 1 depicts the adaptation for atomic information. For a specified R_d imposed by the service and known number of hops from the sink, the desired hop reliability requirement R_{hd} is calculated as:

$$R_{hd} = (Rd)^{1/h} \quad (5)$$

Equation (5) considers a uniform reliability requirement across the hops along $Path_i$. The source node calculates and includes R_{hd} in a message and forwards it to next hop along the path (Algorithm 1: Lines 2-4). When the node forwards a message it first decides whether to send the message or not (Algorithm 1: Line 14). The decision is based on source node's local network condition, i.e. link reliability (R_L) and Rhd as follows:

$$p_s \begin{cases} R_{h_d}/R_L & if\, R_L > R_{h_d} \\ 1 & if\, R_L \le R_{h_d} \end{cases} \quad (6)$$

If $R_L > R_{hd}$ the source node sends the message with probability $p_s = R_{hd}/R_L$ in order to maintain the required reliability. For the case $R_L \le R_{h_d}$ the source node always sends the message. This ensures the proposed solution always adapts to service requirements and maintains the specified service reliability.

When the sensor node decides to send the message it first checks $R_{int} \ge R_{h_d}$, when true it will transmit the message once else the node will calculate the number of transmissions required to attain the R_{hd} (Algorithm 1: Lines 15-21), using Equation (4).

We have chosen probabilistic transmissions [6], i.e. if r=1:34 than the node will do one transmission and then another transmission with a probability of 0:34. Using Equation (7) the approach ensures the desired reliability of information transport across a hop by exploiting spatio-temporal correlation. Each source node knows the total number of source nodes sending the replicated information, e.g. query services may specify the number of nodes reporting the information. In future we explore how to tune the number of source nodes dynamically, i.e. #src.

Proposition 5.1

The minimum number of transmissions for an atomic information entity $\left(T_{\min}^{AI}\right)$ to be delivered with service reliability R_d from Node X to a sink along the path having h hops is:

$$T_{\min}^{AI} = \sum_{x=h}^{0} \frac{\log\left(1-\left(R_d\right)^{1/h}\right)}{s.\log\left(1-p_{\left(X,\dot{X}+1\right)}\right)}$$

Proof:

An information entity generated at Node X is forwarded to the next hop Node X+1 if it has been successfully received regardless of the IACK outcome. Therefore, the information transport only rely on the forwarding probability $p_{(X;X+1)}$, yielding the Proposition 5.1 as a sum over h hops similar to derivation of Equation (7).

Proposition 5.2

The total number of transmissions for an atomic information entity T_{AI} to be delivered with service reliability Rd from Node X to a sink along the path having h hops is

$$T_{AI} = \frac{\log\left(1-\left(R_d\right)^{1/h}\right)}{s.\log\left(1-p_{(x,x+1)}p_{(x+1,x)}\right)} + \sum_{i=h-2}^{1} \frac{\log\left(1-\left(R_d\right)^{1/2}\right)}{s.\log\left(1-p_{(i,i+1)}p_{(i+1,i)}p_f\right)} + \frac{\log\left(1-\left(R_d\right)^{1/h}\right)}{s.\log\left(1-p_{(h-1,0)}p_{(0,h-1)}\right)} \qquad (7)$$

Proof:

The source node transmits until the information entity and its forwarding transmission are both received at node X and X+1 respectively. Following Equation (7), the number of transmissions required at source node is given by:

$$\frac{\log\left(1-\left(R_d\right)^{1/h}\right)}{s.\log\left(1-p_{(X,X+1)}p_{(X+1,X)}\right)} \qquad (8)$$

Algorithm 1: Adaptation for atomic information

```
Data:  Rd, R_L, h, msg, Y_i → ext hop along the path
if source node and atomic information then
calculate R_hd using Equation (5);
msg:R_hd    R_hd;
transport(msg, Y_i);
if forwarding node then
if msg already in buffer then
purge received msg;
R_hd    msg.R_hd;
transport(msg, Y_i);
function transport(msg, Y_i):
check whether to send or suppress using Equation (6);
if send then
calculate r using Equation (7);
send msg to Y_i; if snoop IACK then
purge msg from buffer;
exit();
if suppress then
purge msg from buffer;
end function
```

The forwarded message from Node i successfully received by the next hop Node i+1, may not be overheard by Node i triggering a retransmission. This is accounted for the spatial dependency with conditional probability p_f=Pr[success at i-1 |success at i+1] = Pr[success at i+1| success at i -1].

For h-1< i < 1, assuming proper setting of the retransmission timeouts, the forwarding node, i, transmits until the information entity is successfully received by both, Node i-1 and Node i+1, as well as the forwarding by node i+1 is snooped by Node i. Thus, the number of transmissions is given by:

$$\rightarrow \sum_{i=h-1}^{1} \frac{\log\left(1-\left(R_d\right)^{1/h}\right)}{s.\log\left(1-p_{(i,i+1)}p_{(i+1,i)}p_f\right)} \qquad (9)$$

The sink node, X=0, needs to transmit an EACK. Thus the number of transmissions for last hop will be:

$$\frac{\log\left(1-\left(R_d\right)^{1/h}\right)}{s.\log\left(1-p_{(h-1,0)}p_{(0,h-1)}\right)} \tag{10}$$

Combining Equations (8, 10) yields the Proposition 5.2.

5.4 Adaptation for Composite Information

For composite information, the main challenge is to select the information nodes according to the desired service requirements. For node selection, game theory based solutions [23] are available, since these schemes select the nodes after a certain number of iterations. These approaches cannot be utilized as the information may last for only a short time inside a WSN. Other solutions such as [24] are very application specific. Our approach (Algorithm 2) implements a simple heuristic to randomly select k information nodes in order to meet the desired service reliability. The information nodes can autonomously decide whether to be selected or not according to their probability of selection, i.e. R_d (Algorithm 2: Lines 1-7). The property of uniform random numbers assures that statistically (R_dx100)% information nodes are selected for the information transport.

Sensor nodes first identify the composite information inside the WSNs according to the service specification. For example, tracking services may require some percentage of sensors on the periphery or from information area to report for the coverage [25-26]. Then, each node selects itself from the information area/ periphery according to the service requirements as described in Algorithm 2.

Once the sensor nodes are selected for composite information for information transport, Algorithm 1 starts its functionality to provide desired reliability requirements.

```
Algorithm 2: Composite information transport
Data:  R_d, msg, Y_i → next hop along the path
1      if source node and composite information then
2      i     RAND[0,1];
3      if i>=R_d then
4      NodeSelected = TRUE;
5      transport(msg, Y_i);
```

Proposition 5.3

The minimum and total number of transmissions for a composite information entity T_{CI} to be delivered with service reliability R_d from Node X to sink along the path having h hops is:

$$T^{CI}_{\min} = \left(\sum_{X=h}^{0} \frac{\log\left(1-\left(R_d\right)^{1/h}\right)}{\log\left(1-p_{(X,X+1)}\right)}\right)\eta$$

and

$$T_{CI} = \left(\frac{\log\left(1-\left(R_d\right)^{1/h}\right)}{\log\left(1-p_{(X,X+1)}p_{X+1,X}\right)} + \sum_{i=h-2}^{1} \frac{\log\left(1-\left(R_d\right)^{1/h}\right)}{\log\left(1-p_{(i,i+1)}p_{(i+1,i)}p_f\right)} + \frac{\log\left(1-\left(R_d\right)^{1/h}\right)}{\log\left(1-p_{(h-1,0)}p_{(0,h-1)}\right)}\right)\eta$$

Proof

The derivation of $T^{CI}_{\min}$ and T_{CI} comes directly from the derivation of Proposition 5.1 and Proposition 5.2, with the difference that here s=1, since the sensor nodes are unaware of spatial correlation. The η is the number of source nodes selected probabilistically based on service reliability requirements.

5.5 Acquisition of Network Properties

In order to acquire h and R_d the routing protocol is utilized. The best effort flooding is implemented in such a way that when the node acquire its parent it will rebroadcasts downstream and consequently a stable routing tree is established rooted at the sink. The sink periodically sends beacon messages to all nodes such that a routing tree rooted at the sink is maintained. The sink includes a hop counter to beacon messages, which allows nodes to update their hop count to the sink. In this way all nodes inside a network know how far they are from the sink (in terms of number of hops). Furthermore, a change request for the service requirement on R_d can be disseminated to the sensor nodes, e.g. through piggy backing to beacon messages. This can be further optimized by sending R_d to only a subset of nodes inside the network. In this work we emphasize on information transport from sensor nodes to the sink for ensuring service delivery and not on dissemination of service requirements to sensor nodes. To this end the sink can use existing reliable downstream strategies, e.g. [11, 17, 27] to distribute R_d. Node X keeps track of the link quality between its neighbor Node Y towards the sink using EWMA (Exponentially Weighted Moving Average) [18] as follows:

$$LQ^t = (1-\alpha)*LQ^t + \alpha * LQ^{t-1} \qquad (11)$$

where α is a weighting factor ranging ($0<\alpha<1$) and LQ^t is the latest observation of the link quality in terms of BEP. A node keeps track of BEP between itself and its neighbor node upon reception of a message or when it snoops the channel for IACK. It should be noted that other link quality metrics (Section 7.1) can also be utilized in similar way.

6. EVALUATION

In order to evaluate our approach we first describe the methodology and simulation settings. Next, the performance metrics are defined for a wide representative range of network operational conditions and protocol parameters.

6.1 Methodology and Simulation Settings

The proposed approaches are evaluated based on simulations in TOSSIM [28] simulator. TOSSIM is an event-driven simulation tool widely used in the WSN community. The empirical radio model [18] provided by TOSSIM is utilized. As for routing, RBC uses by default LGR (Logical Grid Routing) [29] protocol, we continue using LGR with the default settings as described in [29]. The code of RBC is available for the mica2 mote platform, consequently it is ported to run under the TOSSIM environment.

The topology used in the simulations consists of a nxn grid topology. The distance between the two nodes is 10 units. The sink is located at one corner. The atomic information is generated from one corner and transported towards the sink. Two cases are chosen, one where atomic information is generated by a single source and another where the atomic information is generated by s sources that are geographically close to each other. For the experiments, 100 atomic information entities are generated with the gap of 3 sec, to be transported towards the sink. Information is generated after 10 sec from the start of the simulation to give enough time for the network to stabilize before an information is generated. For composite information from s sensor nodes, probabilistically η nodes are selected and transported towards the sink. For α a typical value of 0:1 as suggested in [30] is used.

6.2 Performance Metrics

For service availability the performance of information transport protocol is measured as its responsiveness and efficiency. The responsiveness is information transport reliability and timeliness, whereas the efficiency is mainly given by the message complexity.

(1) Information Transport Reliability: The information transport reliability of the protocol is the ratio of number of information entities received by the service/sink to the total number of the information entities generated.

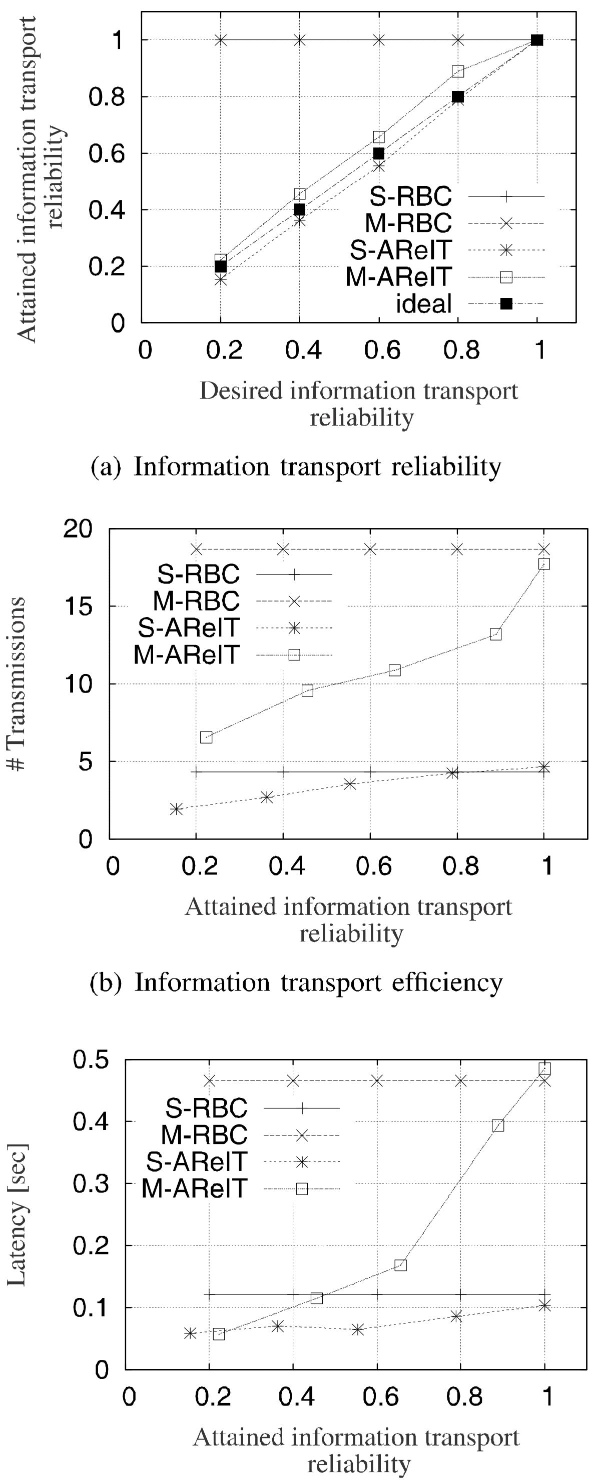
(2) Efficiency: For efficiency the message complexity for an information transport is defined as the total number of message transmissions required for the information to be delivered to the service (including the retransmissions).

(3) Timeliness: The timeliness of information transport protocol is defined as the time elapsed from the generation of the first information entity to the arrival of the first information entity at the sink. The timeliness of the protocol is the average of information transport latencies of all generated information entities.

6.3 Simulation Results

Fig. 4 shows the adaptation of our approach for variable service requirements. Fig. 4(a) depicts the reliability attained by RBC and AReIT when the single node (S-RBC, S-AReIT) and multiple nodes (M-RBC, M-AReIT) are sending the atomic information to the sink. We observe that S-AReIT and M-AReIT attains desired reliability with slight difference. The reliability attained by S-RBC and M-RBC is constant. Fig. 4(b) shows the total number of transmissions required to attain the information transport reliability. The number of the transmissions for S-RBC and M-RBC do not change. The number of transmissions vary for S-AReIT and M-AReIT in proportion to the attained level of reliability. We observe that M-AReIT has relatively less number of transmissions than M-RBC because our approach explicitly integrate the spatial redundancy of sensor nodes. Generally, AReIT adapts to the desired service requirements with less number of transmissions than RBC. Fig. 4(c) shows the timeliness of RBC and AReIT. The latency of AReIT is well below the RBC for providing attained service reliability. For higher service reliability requirement (100%), AReIT behaves similar to the RBC in terms of the efficiency and timeliness which shows that in this extreme case AReIT does not perform worse than RBC. On the other hand for all other cases AReIT outperforms RBC with respect to responsiveness and efficiency.

Fig. 5 evaluates the robustness of RBC and AReIT against evolving network conditions. In this scenario 80% service reliability requirement is assumed. Fig. 5(a) shows the information transport reliability for varying BEP. S-AReIT and MAReIT cope with the evolving network conditions



(a) Information transport reliability

(b) Information transport efficiency

(c) Information transport timeliness

FIG. 4. ADAPTATION TO SERVICE REQUIREMENTS FOR ATOMIC INFORMATION

and provide desired service requirement with (+/-) 2% whereas S-RBC and M-RBC are not able to cope with evolving network conditions and provide high reliability for good network conditions (BEP 0:0 - BEP 0:01) and less reliability for bad network conditions (BEP 0:02). For BEP 0:02 M-AReIT and S-AReIT utilize more transmissions owing to the adaptation to bad network conditions by increasing number of retransmissions (Fig. 5(b)). On the other hand S-RBC and M-RBC after fixed number of retransmissions failed to transport the information, thus resulting in less number of transmission with less than desired reliability. This also impacts the timeliness of AReIT as shown in Fig. 5(c). At BEP 0:02 the latency of S-AReIT and M-AReIT is higher than S-RBC and M-RBC, but it is directly related to the number of transmissions and attained reliability. In general, AReIT maintains the desired reliability with higher number of transmissions and higher latency when BEP is high.

Fig. 6 depicts the impact of information nodes for atomic information. In this scenario we assume that service requirement for information transport is 80%. Fig. 6(a) shows the information transport reliability for varying number of information nodes. As the number of information nodes increases the reliability of RBC decreases, since it do not exploit the spatial redundancy of the information resulting in more collisions. In contrast, AReIT adapt according to number of source nodes resulting in less collisions and maintaining the desired reliability. The collisions for RBC trigger the retransmissions resulting in higher number of overall transmissions compared to AReIT as shown in Fig. 6(b). It is observed that the number of transmissions for AReIT are always less than RBC and with the increasing number of information nodes it is more evident that AReIT efficiently achieves the desired service requirements and exploit spatial correlation. Fig. 6(c) shows the impact of more transmissions with high latency of RBC compared to AReIT. AReIT do not use any explicit timeliness mechanisms but its lower latency shows the impact of appropriately using the spatial correlation.

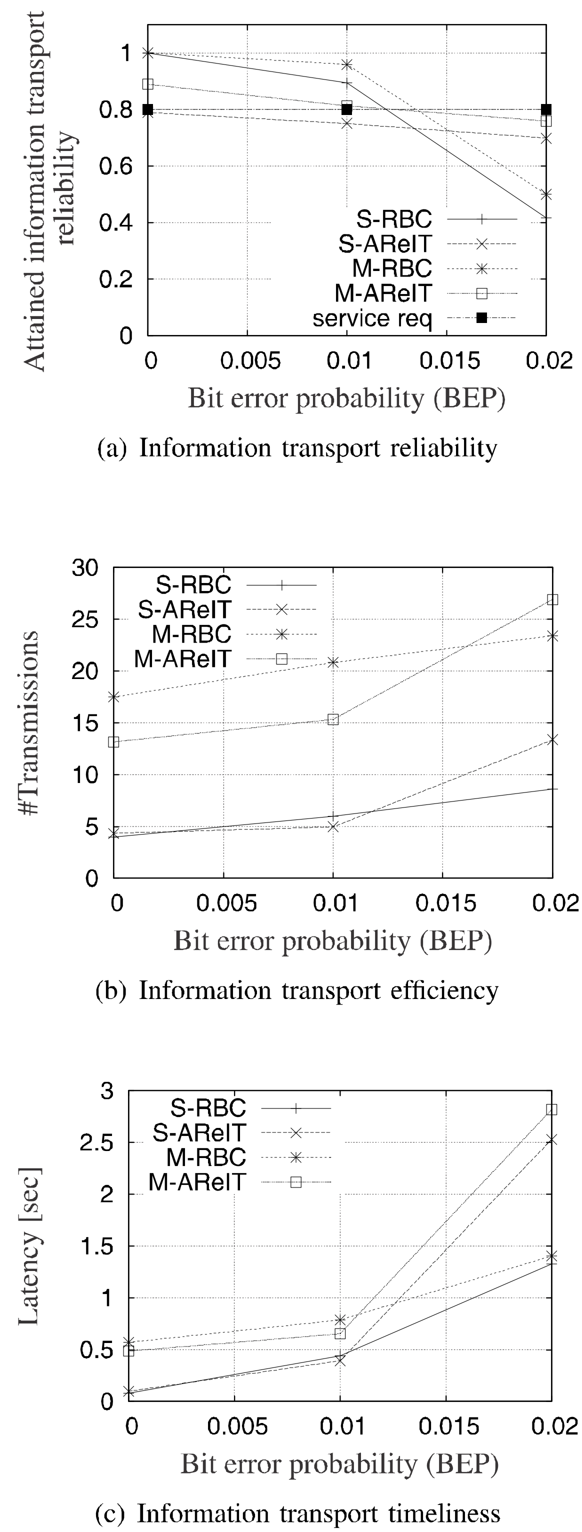
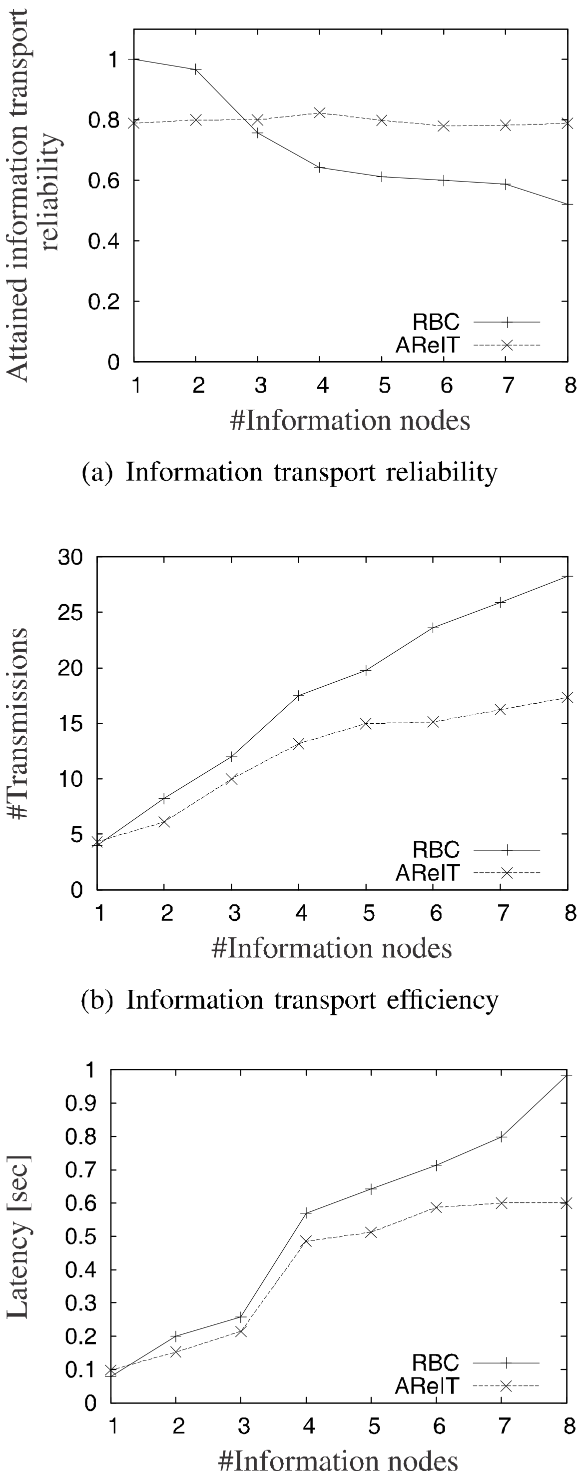


FIG. 5. ADAPTATION TO NETWORK CONDITIONS FOR ATOMIC INFORMATION (R_d=0:8)



(a) Information transport reliability

(b) Information transport efficiency

(c) Information transport timeliness

FIG. 6. IMPACT OF NUMBER OF INFORMATION NODES FOR ATOMIC INFORMATION (R_d=0:8)

Fig. 7 depicts the impact of information nodes for composite information. In this scenario also 80% service requirement for information transport is considered. Fig. 7(a) depicts the reliability of composite information. AReIT adapt according to type of information and selects the nodes for information transport. As the number of nodes increases the reliability also increases because for composite information the number of sensor nodes is unknown and all selected nodes have to transport the information. With the increase in number of nodes their selection probability also increases, thus resulting in higher reliability. RBC reliability decreases with increase in number of nodes because of higher number of collisions as in the case of atomic information. Similarly, the efficiency and latency of RBC is higher than the AReIT for composite information which shows that AReIT is more robust than RBC (Fig. 7(b-c)).

6.4 Observations

The different simulations have quantified the viability of AReIT approach. In the light of the experimental analysis we make the following observations:

- Different service classes impose different reliability requirements for service delivery, thus the protocol should adapt accordingly. AReIT shows its capability of providing service specific reliability (Fig. 4(a)) and outperforms the RBC protocol.

- In WSN perturbations are norm rather than exception and providing reliable service delivery is difficult. We observed the AReIT capability to cope with harsh environments where network connectivity is fluctuating (Fig. 5(a)). In such conditions AReIT exploits the temporal redundancy (retransmissions) according to the current state of the network and maintains the desired information transport reliability.

- The information availability at the sink is important for reliable service delivery. AReIT manages information availability by exploiting spatial and temporal redundancies inside the network according to the service requirement and evolving network conditions. AReIT achieves this by efficiently tuning the number of retransmissions and adapting according to the number of sources.

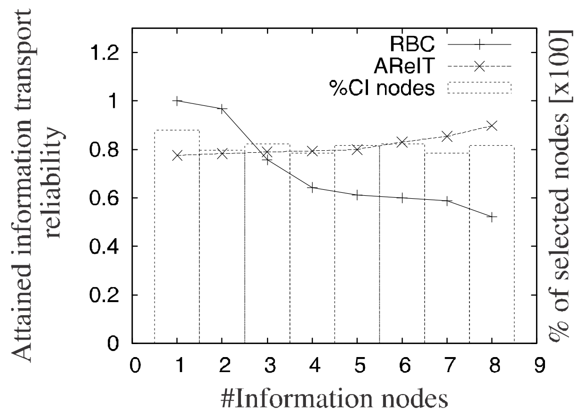
- For the reliable service delivery, timeliness plays an important role. Information not reaching in timely fashion is useless for a service, thus hindering the service delivery. Figs. 4(c)-7(c) show that AReIT provides the required information transport reliability with timeliness.

- Generally, it is observed that there is a tradeoff between efficiency and timeliness to provide reliable service delivery. For example, at BEP 0:0 less transmissions are carried with low latency. On the other hand at BEP 0:02 more transmissions are required leading to higher latency. Our approach saves valuable retransmissions by maintaining the desired reliability and avoiding over performance.

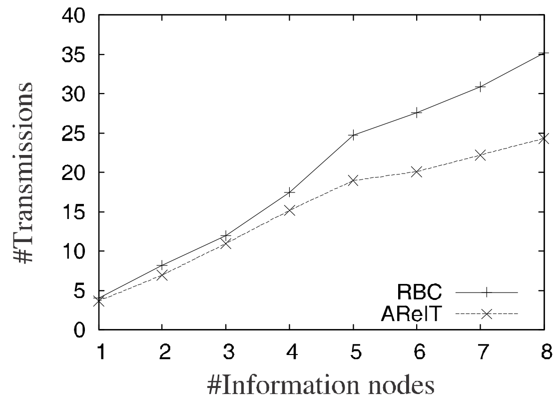
- It is also observed that AReIT adapt efficiently with increasing number of source nodes for atomic and composite information.

7. CONCLUSION & FUTURE WORK

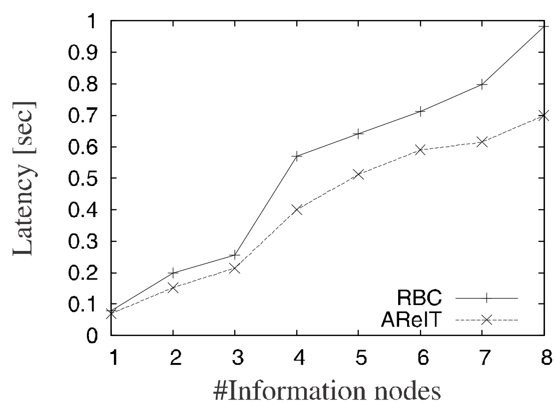
We have presented an AReIT approach which provides dynamic tuning of retransmission to overcome perturbations along with integrated spatial correlation for the information transport. AReIT is capable of adapting to different service requirements by exploiting temporal and spatial redundancies as discussed in Section 6.4. In future we are looking to explore more link quality metrics and to analyze the impact of these metrics on the information transport reliability. Also we are looking for different mechanisms where source nodes locally and dynamically learn about the number of sources sending the information towards the sink.



(a) Information transport reliability



(b) Information transport efficiency



(c) Information transport timeliness

FIG. 7. IMPACT OF NUMBER OF INFORMATION NODES FOR COMPOSITE INFORMATION (R_d=0:8)

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