A Comparative Study of Data Transport Protocols in Wireless Sensor Networks*

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Abstract

Several proposals describing transport layer protocols for sensor networks appear in the literature. As each proposal is typically evaluated in the context of carefully selected parameters and scenarios, the benefits can be subjective. Also, given the limited details available of different proposals, it is difficult for developers of sensor network applications to select from the range of alternative transport protocols. This paper develops a common basis for evaluation of varied proposals. We first classify and review the existing protocols and evaluate them by measuring their performance in terms of responsiveness and efficiency in a conformal simulation environment and for a wide range of operational conditions. Common sources of poor performance are identified. Based on this experience, a set of design principles for the designers of applications and future transport protocols is presented.

1 Introduction

Wireless sensor networks (WSNs) constitute a rapidly growing research area, covering both a wide variety of devices and applications. Typical applications involve tracking or monitoring, either statically as embedded sensors or dynamically as mobile (semi-) autonomous entities. Correspondingly, applications such as monitoring of traffic, disaster surveillance and target detection are seeing increased use of WSNs. Generally a WSN comprises number of sensor nodes possessing limited processing and power capabilities, often communicating over unreliable and low bandwidth radio links [2]. Empirically, the core operation of a WSN is to detect an event of interest from the environments and to transport it to a gateway node termed as *sink*. A primary design objective of data transport (DT) protocols is to enhance the *responsiveness* of the WSN, i.e., event report reliability and timeliness.

There are several DT protocols in the WSN literature, with varied semantics and design objectives. Existing protocols are often evaluated for a limited subset of possible scenarios and parameters, although the actual design space is very large. This makes it difficult to compare and evaluate the DT protocols due to differing assumptions made by the designers. This also makes it hard to distinguish whether the results are true differences between the protocols or they are only due to different experimental setups used. Although some surveys on DT protocols exist [2, 19, 20], there is no comparative performance study of these protocols. Such a study would (1) provide useful insights on operations of DT protocols and their design choices, (2) aid development of more efficient and robust DT protocols by understanding the design and operational factors, and (3) allow for more widespread adaptation of DT protocols by showing which design choices are appropriate for a given network scenario.

This paper targets three specific objectives. First, we do a categorization of existing protocols based on their targeted application scenarios and their semantics, and compare sample protocols in each category. Second, we conformally compare the DT protocols over a wide range of protocol parameters such as source redundancy and maximum number of allowed retransmissions, as well as network conditions including number of nodes, network connectivity, link quality and underlying routing protocols. Third, we identify areas where the protocols perform well and where they show deficiencies.

The rest of the paper is organized as follows. Section 2 presents the categorization of DT protocols and selection of appropriate representative from each class. Section 3 details the proposed comparison framework. The simulation results of selected DT protocols are presented in Section 4. The discussion based on our results is presented in Section 5. Our conclusions appear in Section 6.

2 Categorization of DT Protocols

Recent surveys [2, 19, 20] classify DT protocols into *downstream* and *upstream* protocols. Downstream protocols transport data from the sink to the source nodes, whereas upstream protocols transport data from sensor

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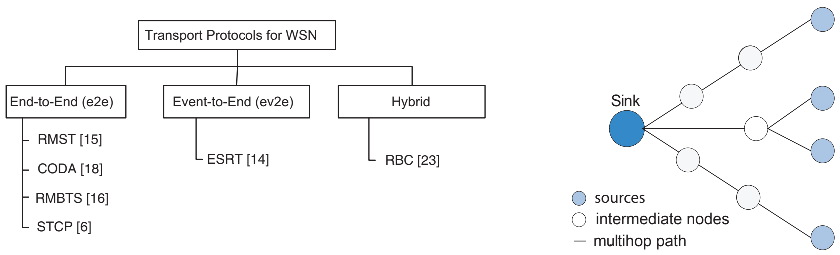


(a) Upstream transport protocols (b) Generalized semantics

Figure 1. Classification of DT protocols

nodes to the sink. In downstream protocols, communication is one-to-many whereas upstream communication is many-to-one. In this paper we will focus on upstream protocols given the data centric nature of WSNs and due to the fact that many applications primarily target collecting events from the environment for making decisions. A prominent semantic used for DT in traditional WSN is the *end-to-end (e2e)* data delivery, where a node has to transport the data towards the sink. This semantic is not very suitable for WSNs [14], as generally WSN rely on collective effort of several nodes. The commonly accepted semantic by the research community is *event-to-end (ev2e)* [7, 14, 23]. This semantic considers multiple nodes reporting the event to the sink. Each node that detects the event is responsible for sending the data to the sink. This semantic is shown to be more suitable than the e2e semantic for WSN [14]. Based on these semantics we classify the upstream DT protocols into three primary categories *e2e, ev2e and hybrid* DT protocols as shown in Fig. 1(a). Fig. 1(b) shows the generalized DT semantic where a number of sources transmit event messages towards the sink. The e2e semantic is a special case of the ev2e semantic, i.e., where the number of source nodes is one.

2.1 The e2e Class

The main objective of e2e DT protocols is to efficiently maximize the responsiveness. To achieve these objectives DT protocols have to mitigate packet loss and network congestion. For packet loss, *retransmission strategies* are used and for network congestion appropriate *congestion control mechanisms* are deployed.

Retransmission Strategies: Retransmissions are required to overcome message loss, i.e., if the message does not reach the sink. To enable retransmissions it is necessary to detect the message loss. Several *message loss detection (MLD)* techniques can be adopted by DT protocols such as Acknowledgment (ACK), Negative ACK (NACK), Implicit ACK (IACK), Selective ACK (SACK), Selective NACK (SNACK) and timers. In comparison with wired networks, where only the source caches messages and retransmissions are done end-to-end, in WSN hop-by-hop retransmissions are more feasible [17]. If only the source caches and retransmits, the retransmission strategy is termed *end-to-end*. If the intermediate nodes also cache and retransmit, the strategy is termed *hop-by-hop*. This poses the problem of where to cache the packet on the way from sources to the sink, either all intermediate nodes on the path or a subset of them should cache.

Congestion Control Mechanisms: These comprise schemes to detect congestion, and alternatively to avoid or mitigate it. In the WSN literature, we identify the following congestion detection (CD) schemes. The first approach is to monitor the channel utilization, e.g., through observing the collision rate [18]. The second approach is to monitor the buffer utilization, e.g., by observing the buffer length [14] or the average message queuing time. Upon congestion detection, nodes trigger congestion notification by disseminating the appropriate information to the relay nodes and the sources. Source nodes realize congestion avoidance (CA) by dynamically adjusting their data rate. The common approach for the adjustment is Additive-Increase and Multiplicative-Decrease (AIMD) [14, 18]. Some approaches propose to conduct the adjustment in a discriminative manner depending on the fidelity of the source.

Existing e2e DT Protocols: Most existing e2e DT protocols address retransmission and congestion control separately. Some protocols [12, 15] propose a strategy to detect message loss and fix the nodes that cache the packets for the purpose of required retransmission. Other protocols [18] propose a mechanism to mitigate congestion. Table 1 compares the existing e2e protocols.

Reliable Multi-Segment Transport (RMST) [15] is a SNACK based protocol, it places responsibility for message loss detection at the receivers (which can be intermediate nodes as well as the sink). Missing fragment requests are uni-cast from the sink to the source. In-network caching allows fast recovery. However, in the worst case, the repair request needs to travel all the way to the source. RMST lacks congestion control. In [18] the authors have developed a congestion control transport protocol called *Congestion Detection and Avoidance (CODA)*. It has three components: congestion detection, open-loop hop-by-hop back-

	Retransmission		Congestion Control	
	MLD	**CP**	**CD**	**CA**
RMST [15]	SNACK	source+intermediate	–	–
CODA [18]	–	–	buffer + channel	AIMD
RMBTS [16]	NACK	source	–	–
STCP [6]	ACK, NACK	source	buffer	AIMD

Table 1. Comparison of existing e2e protocols

pressure, and closed-loop end-to-end multi-source regulation. CODA attempts to detect congestion by monitoring current buffer occupancy and wireless channel load. In [16] the authors proposed the *Reliable Multihop bulk Transfer Service (RMBTS)*. The protocol uses NACK-based end-to-end flow control scheme. The nodes update there next hop for forwarding the data based on the reliability scores gathered by continues monitoring of route. *Sensor Transmission Control Protocol (STCP)* [6] implements both congestion control and reliability in a unified protocol. It allocates most responsibility to the sink. Intermediate nodes detect congestion based on queue length.

In this work we focus on retransmission strategies and not on the congestion control mechanisms. We plan a similar comparative study of CD and CA mechanisms in the future. The e2e protocols are similar in nature and differ only in the approaches for message loss detection (MLD), cache points (CP), CD and CA techniques. Therefore instead of focusing on different e2e protocols we consider a skeleton (SKE) protocol comprising hop-by-hop retransmission strategy, which is the most reliable and efficient [15, 17] with CP at all intermediate nodes.

2.2 The ev2e Class

The class of ev2e DT protocols contains noticeably one protocol, i.e., the *Event to Sink Reliable Transport (ESRT)* [14]. We detail this protocol and discuss our implementation choices. The ESRT protocol maintains application specific reliability. It achieves the optimal operating point by adjusting the reporting rate of sensor nodes depending upon current network load. In this approach, upon getting information from nodes about current network state, the sink accordingly adjust the reporting rate of source nodes. In ESRT, each node that detects an event routes the data towards the sink. ESRT has been developed for continuous-event-flow applications, where an adaptation of the data report rate makes sense. However, this adaptation is less useful for bursty-data-flow applications as events occur independently from each other spontaneously and at random places in the network. Thus the event report reliability of two different events are independent.

The ev2e protocols implement a many-to-one process, where the number of relay nodes decreases continuously along the way towards the sink. This results in higher bandwidth requirement for nodes closer to the sink. In the literature some solutions have been presented such as [24] which explore the aggregation and duplication of data. We investigate the performance of the ESRT protocol without considering these optimizations.

2.3 The Hybrid Class

In this class one primary protocol is identified, namely the *Reliable Bursty Convergecast (RBC)* protocol [23]. RBC deploys the hop-by-hop reliability as known from the e2e semantic on top of the ev2e semantic. The RBC protocol provides message reliability through hop-by-hop retransmission based loss recovery. The RBC reliability design is based on a windowless block acknowledgement and IACK. RBC proposes intra- and inter-node message scheduling to avoid retransmission-based collisions and congestion. RBC increases the event report reliability by implementing the ev2e semantic, i.e., more than one source node report the same event.

The RBC protocol has been developed for bursty-data-flow-driven safety-critical applications, where the requirements on the responsiveness of the WSN is relatively high. We will consider RBC in this study for comparison with other classes.

3 Protocol Comparison Framework

In order to compare the existing DT protocols we first describe our methodology and simulation settings. Then we define the performance metrics, and classify the scenarios into five main studies to cover a wide representative range of network operational conditions and protocol parameters.

3.1 Methodology and Simulation Settings

We compare the selected DT protocols based on simulations that we have conducted using the TOSSIM [9] simulator. TOSSIM is an event-driven simulation tool widely used in the WSN community. We have used the empirical radio model [21] provided by TOSSIM. In this model, a sensor node sends and receives messages using an error distribution based on empirical data, where bit errors depend on distances from sender to receiver and background noise.

Furthermore, to compare the DT protocols the underlying protocols in sensor network stack are considered as well.
MAC Protocol considerations: For MAC the major distinction is between the use of TDMA or CSMA to resolve channel access. In this paper, we focus on CSMA-based implementations, because, although several TDMA protocols have been proposed [5, 13], their implementation in TOSSIM is not available. Under CSMA-based implementations BMAC [11] and SMAC [22] are widely used MAC protocols [10] for TinyOS. Only BMAC implementation is available in TOSSIM for simulation. Therefore, we had to limit ourself to BMAC [11]. BMAC in principle, uses low-power listening to save energy. Since we do not monitor energy efficiency, we simply use the default setting of always keeping the radio on. The MAC layer itself does not perform any retransmissions, but notifies the routing layer above of missing acknowledgements for uni-cast traffic.
Routing Protocol considerations: Fundamentally, there are two major classes in routing, i.e., *reactive* and *proactive* [3]. Reactive protocols find the route only when there is data to be transmitted. Proactive protocols on the other hand, find paths in advance for all source and destination pairs and periodically exchange topology information to maintain them. In literature there are several proactive routing protocols [3]. As for routing the messages, RBC uses by default Logical Grid Routing (LGR) [4] protocol, which is the representative proactive routing protocol, we have chosen LGR for routing the messages for proactive class. For LGR we use the default settings as described in [4]. The reactive class consist of several protocols in literature [3]. We have chosen TinyAODV [1] a representative because it is the only available reactive protocol in TinyOS repository and also it is a ZigBee standard routing protocol. For TinyAODV we have used the default settings. The code of RBC is available for the mica2 mote platform, consequently we ported the RBC code to run under the TOSSIM environment. Since the code for e2e protocols and ESRT is not available, we implement SKE and ESRT in TOSSIM. We extracted the retransmission strategy from RBC [23] and used it as a basis for the SKE protocol.

The topology that we used in our simulation experiments consists of typically used n x n grid topology. The distance between the two nodes is denoted as the *cell size*. The sink is available at the upper left corner. In case of ESRT and RBC protocols, s nodes from each of each of the remaining three corners of the grid, that are geographically close to each other, generate an event message to be transported to the sink as shown in Fig. 2. For SKE which is a represented e2e protocol, where one node is sending data towards the sink, we assume some local signalling as a complementary to SKE such that instead of s nodes, a single node from each corner send event information.

In our experiments three events are generated simultaneously to be transported towards the sink. Two protocol parameters are of primary concern for DT protocols, i.e., number of sources s and number of maximum retransmissions r. In this work we assume $s = 4$ for ESRT and RBC protocols, whereas for SKE $s = 1$. RBC uses $r = 3$ by default and to enable a conformal comparison between e2e and ev2e protocols, we set the maximum number of retransmission for the SKE protocol equal to the number of sources of ESRT and RBC, i.e., $r = 4$. An event message is generated after 40 sec from the start of the simulation to give enough time for the network to stabilize before an event is generated. We assume that an event can be reported as a single message and if the sink receives at least one event message, the event is considered to be detected.

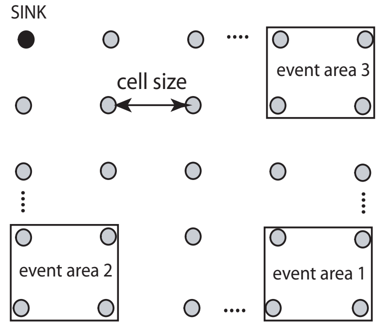


Figure 2. Scenario settings (n x n grid)

3.2 Performance Metrics

The performance of DT protocols is commonly measured as protocol responsiveness and efficiency. The responsiveness of the protocol is defined by event reporting reliability and timeliness, and the protocol efficiency is mainly given by its message complexity.
Responsiveness: The responsiveness of a DT protocol is its ability to report an event to the sink with a high fidelity and in time. To compare the responsiveness of the different DT protocols, we measure separately their event report reliability and timeliness.
Event Report Reliability: The event report reliability R of the protocol is the ratio of detected events to the total number of generated events.
Timeliness: The timeliness of DT protocol is defined as the time elapsed from the generation of the first event message to the arrival of the first event message at the sink. The timeliness of the protocol is then the average of event report latencies of all generated events. Since some events may not be reported at the sink, we do not consider those messages in the calculation of the average event report latency.
Efficiency: The efficiency of a DT protocol is commonly measured as its message complexity. We define the message complexity of a DT protocol as the total number of

transmissions required for the event messages to be delivered to the sink, including the retransmissions. We note here that communication between nodes is regarded as the highest energy consuming factor. Therefore, this metric can be utilized to estimate the energy consumption of the protocols.

3.3 Description of Comparative Studies

We measured the values of the above described metrics depending on the network properties, routing protocols and DT parameters. We base our comparison on the five studies. In each study, we investigate the impact of relevant network property on the responsiveness and efficiency of the SKE, ESRT and RBC protocols. The considered network properties include number of nodes, network connectivity and bit error probabilities (BEP). Furthermore, we tune the most relevant protocol parameters and suggest adaptation issues for these parameters. Unless specified, we have used LGR as underlying routing protocol.

Study 1: Impact of Network Scale The purpose of this study is to investigate the ability of the protocols to maintain the responsiveness and efficiency as the number of nodes varies. Scalability is always a concern for protocol designers, and this study enables us to observe the scalability of protocols. Furthermore, varying the number of nodes reflects the different operational situations occurring in WSN, e.g., node crash, re-deployment of nodes and duty cycling. In [21] the authors have shown that nodes having a maximum communication range of 50 feet, have good connectivity between them only when they are 7.5 feet apart. Nodes having distances over 7.5 feet experience transient connectivity. For this study we set the *(cell size)* to 7.5 feet, to have good number of neighbors per node.

Study 2: Impact of Network Connectivity The main objective of this study is to show the robustness of the protocols to network connectivity changes. For this study we change the network connectivity by varying cell sizes from 2.5 to 20 feet. As we increase the cell size, a node has limited connectivity to its neighbors.

Study 3: Impact of Bit Error Probability The objective of this study is to show the robustness of the protocols to varying link qualities. This is crucial for WSNs since the link quality may change during the lifetime of the application. We consider the wireless channel BEP, which varies the link reliability and latency. In wireless communication, sometimes quite high average BEP from 10^{-4} to 10^{-2} is possible [8]. In this work we vary the BEP between a node and its neighbors from 0 to 3 x 10^{-2}, reflecting a wide range of cases. This study also covers the scenarios, where the network is congested. Collisions and congestion leads to corruption of packets, which is similar to corruptions of bits.

Study 4: Impact of Routing Protocols Existing DT protocols assume the existence of a routing protocol. Designers in general evaluate their protocols for their favorite routing protocol. In a recent comparative study [10], the authors showed that there is no routing protocol that outperforms all others in all network conditions. Therefore a deeper analysis of the impact of routing protocols on the performance of DT protocols is of a great interest. In this study we investigate the impact of reactive routing protocols on responsiveness and efficiency of DT protocols and compare it with proactive routing protocols.

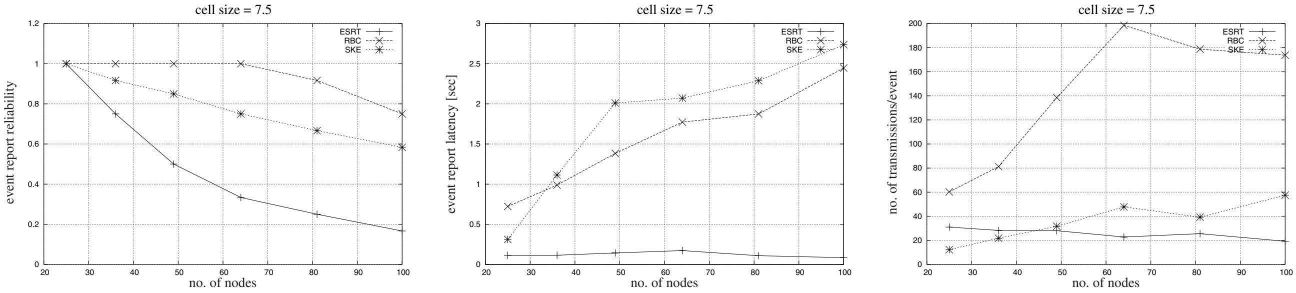
Study 5: Tuning DT Protocol Parameters We investigate the impact of tuning DT protocol parameters for responsiveness and efficiency. For this study we take RBC as the reference protocol and tune parameters for ESRT and SKE. RBC uses $s = 4$ and $r = 3$, so in the worst case altogether 12 retransmissions takes place for each event. Accordingly, we tune for the SKE protocol ($r = 12$) to have the same maximum number of transmissions for a single event. It should be noted that for SKE we can not tune s, as for SKE only one source is available. We term this tuned SKE protocol SKE-3x. To increase the reliability of event reporting the authors of ESRT [14] suggest to increase the data rate. Therefore, for ESRT we kept $s = 4$ and increased the data rate to 3 messages per event per source instead of 1 event message per source. We term this version of ESRT as ESRT-3x. The approach here is to investigate which protocol parameters are suitable to achieve higher event report reliability. Either we increase the data rate for an event or we increase the maximum number of retransmissions to achieve higher event report reliability.

4 Evaluation

In this section we discuss the results of simulations that were conducted for the selected protocols.

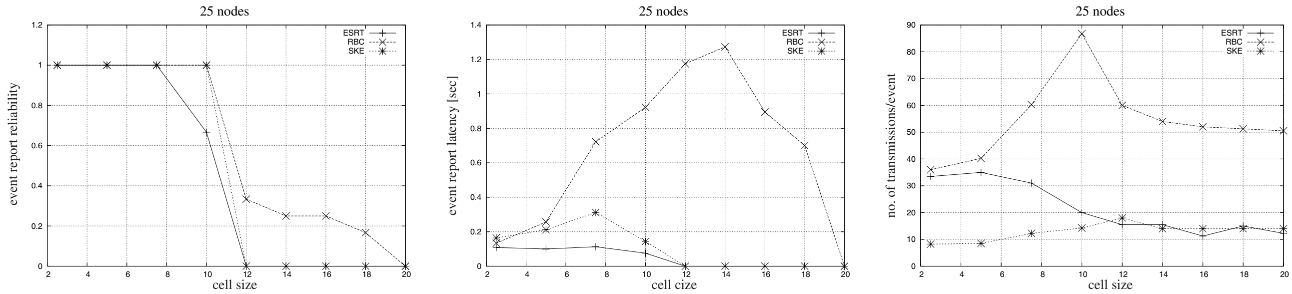
4.1 Impact of Network Scale

Fig. 3(a) displays the observed event report reliability for each of the selected protocols for different number of nodes (from 5x5 to 10x10 grid topologies) while fixing the cell size to 7.5 feet. We examine that as the number of nodes increases, the event report reliability tends to decrease and none of the protocols shows 100% event report reliability. This is due to the fact that the number of hops are increased between event sources and the sink. However, RBC's event report reliability remains always higher than ESRT and SKE. The event report reliability of ESRT is decreasing gradually as the number of nodes increases because ESRT is not retransmitting the lost packets. With increase in number of hops the probability of packet loss increases, thus reliability decreases with the number of hops. Similarly, the event report reliability of SKE and RBC also decreases gradually with network scale. Fig. 3(b) shows that with an increase in number of nodes, the latency is also increased. This is also expected as with the increase



(a) Event report reliability (b) Event report latency (c) Event report efficiency

Figure 3. Impact of network scale



(a) Event report reliability (b) Event report latency (c) Event report efficiency

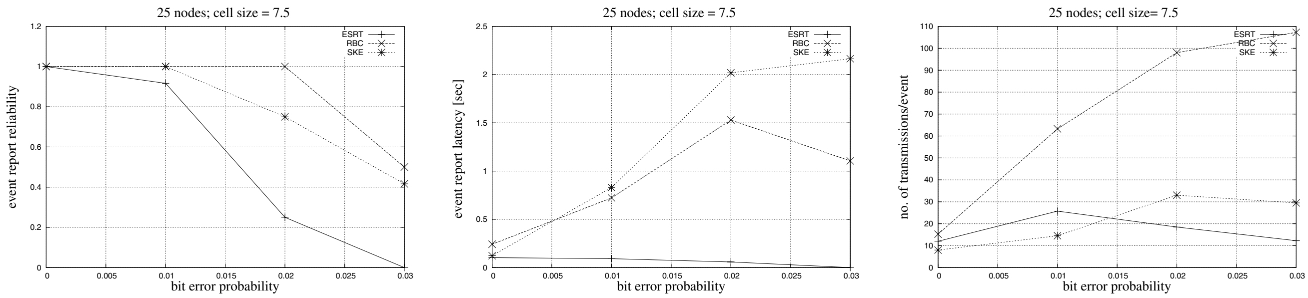
Figure 4. Impact of network connectivity

of number of nodes, the number of hops also increases between source nodes and the sink, thus the event messages are passing through more nodes. This behavior is specific to the underlying routing protocol that chooses nodes's parent in the spanning tree based on number of hops. In this way a message takes more time to reach the sink. ESRT's latency always remain low which is directly related to low event repot reliability. On the other hand, SKE's latency is in most cases highest corresponding to the fact of low number of sources reporting an event and reliability is reached by successive retransmissions. RBC uses the highest number of transmissions compared to ESRT and SKE as shown in Fig. 3(c). For RBC, the number of transmissions tends to increase as the number of nodes increases since more intermediate nodes are retransmitting the event messages. For SKE the number of transmissions are less for fewer number of nodes and as the number of nodes increases, SKE's number of transmissions increases owing the increase in number of hops. For ESRT the number of transmissions are always less, which corresponds to the fact of decrease in event report reliability.

4.2 Impact of Network Connectivity

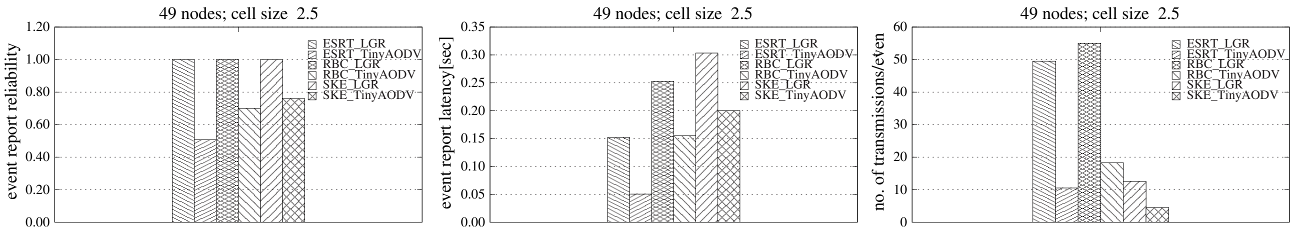
We performed the experiments for various number of nodes. Due to space limitation we are presenting a subset of results as they show similar trends. Fig. 4 shows the event report reliability, latency and efficiency for 25 nodes at different cell sizes.

Fig. 4(a) shows the RBC protocol is performing better than ESRT and SKE with respect to event report reliability owing to the use of retransmissions and acknowledging mechanisms. When the nodes have good connectivity all three protocols are showing high event report reliability. We also observe that as the network connectivity decreases the event report reliability also decreases. RBC is always more resilient than ESRT and SKE. The SKE protocol is performing well compared to ESRT, owing to the hop-by-hop retransmission strategy. Whereas for ESRT, once a message is lost, it is lost forever. In all cases we observe that beyond a cell size of 10 feet the protocols are not performing well with respect to event report reliability, suggesting that these protocols are not suitable for networks to be deployed in lower network connectivity. From Fig. 4 (b) we conclude that the latency of the ESRT is the lowest. The latency values should be interpreted together with the event report reliability. RBC and SKE show higher latencies since they retransmit the message at intermediate hops. The latency of SKE is relatively less than RBC, as SKE has fewer event reporting sources. In general, as the network connectivity decreases the latency of RBC and SKE increase due to the fact that both protocols have to retransmit the messages more times, to be reported to the sink. The latency of RBC



(a) Event report reliability (b) Event report latency (c) Event report efficiency

Figure 5. Impact of bit error probability



(a) Event report reliability (b) Event report latency (c) Event report efficiency

Figure 6. Impact of routing protocols

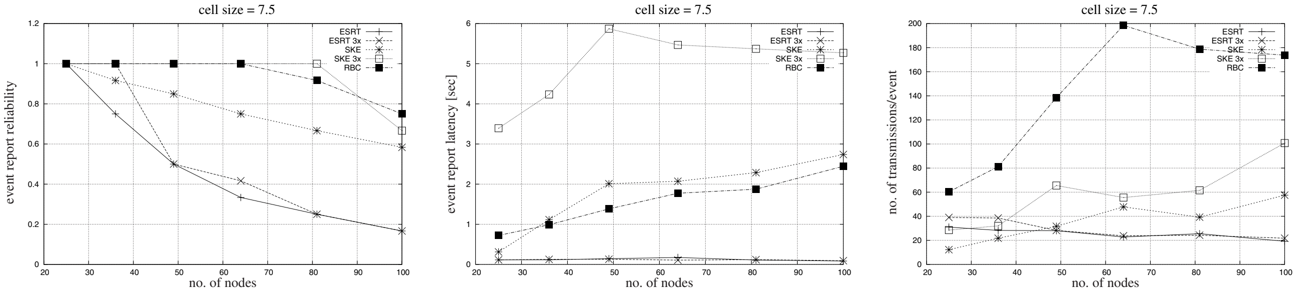
and SKE start decreasing as network connectivity is getting worse because the number of successfully reported events is lower. As expected the number of transmissions for RBC is always higher than ESRT and SKE as shown in Fig. 4(c) especially for large cell sizes. We observe that for higher network connectivity SKE is more efficient, but as the network connectivity decreases, the number of retransmissions are slightly increases as the nodes have limited connectivity with their neighbors. We also observe that as network connectivity starts to decrease, the number of transmissions increases for RBC because all nodes along the path are retransmitting to achieve higher event report reliability. Beyond cell size 10 feet the number of good neighbors decreases and thus the reliability of route towards the sink becomes lower, resulting in less number of transmissions for RBC. Similar effect is observed for ESRT and SKE as well.

4.3 Impact of Bit Error Probability

We performed simulations for varied number of nodes. As trends are independent of number of nodes and similar, we here include the simulations for 25 number of nodes only. Fig. 5(a) shows that as BEP is increased, the event report reliability is decreased. For lower bit error probabilities, all protocols perform equally well. SKE and RBC perform well at high bit error rates compared to ESRT. This suggests that these protocols perform well in erroneous conditions with collisions and high contention, and shows their robustness against these problems. At lower BEP the latency of ESRT is low (Fig. 5(b)) out-performing SKE and RBC because ESRT does not implement a retransmission mechanism. This shows that at lower BEP the overhead of retransmission can be avoided. We observe that at a higher BEP the latency of SKE is much higher than that of RBC owing to the less number of sources. In general as the BEP increases, the latencies of SKE and RBC increase. Fig. 5(c) shows that the efficiency of RBC decreases at high BEP, but this is the cost of its high event report reliability. At low BEP, SKE is more efficient owing to the fact that one node is sending the event information. With increasing BEP the number of transmissions also increases to maintain higher event report reliability. For ESRT, at lower BEP the number of transmissions slightly increases and as BEP increases the number of transmissions decreases due to the fact that at higher BEP, ESRT is unable to forward the message and message gets lost.

4.4 Impact of Routing Protocols

Fig. 6 (a) shows the impact of changing the routing protocol on event report reliability for 49 nodes and cell size of 2.5 feet. We observe that using LGR the event report reliability of all DT protocols is 1 whereas the use of TinyAODV provide the event report reliability between 0.5 to 0.75. This is due to the fact that TinyAODV uses flooding for route discovery, and for some nodes either route request (RREQ) or route reply (RREP) gets lost because of collisions. Therefore, these nodes could not establish a route to



(a) Event report reliability (b) Event report latency (c) Event report efficiency

Figure 7. Impact of tuning DT protocol parameters

the sink. We also noticed that the event report reliability was high when a route was in the local cache of a node. This suggests that the routing success rate is driven by the efficacy of route establishment. Since routes are established via flooding, the higher the number of sources trying to establish routes, the lower the likelihood of a route to be established successfully. Subsequently, the event report reliability of SKE is higher than that of other DT protocols when using TinyAODV suggesting that the reactive protocols are not suitable for event driven applications where simultaneously more nodes are sending event information towards the sink. Fig. 6(b) and Fig. 6(c) show the latency and efficiency of DT protocols for different routing protocols respectively. We notice that latency and efficiency of TinyAODV are lower compared to LGR which correlates with its lower event report reliability. Furthermore, the latency and efficiency are related with the route length and the quality of its links. We observe that TinyAODV selects the forwarding node from which it gets RREP irrespective of its link reliability and thus the route is shorter and has lower reliable links. LGR takes care of quality of links by periodic beaconing and selecting more reliable neighbors to forward the data which leads to longer route. This results in more transmissions and increased latency for LGR, but higher event report reliability. If an initially found route is unreliable TinyAODV generate new RREQ which further degrades the performance of DT protocols.

4.5 Tuning DT Protocol Parameters

Now we investigate the impact of tuning the protocol parameters on the responsiveness and efficiency. Fig. 7(a) shows that by allowing SKE-3x to retransmit more, the event report reliability is increased significantly. Whereas ESRT-3x, while sending more messages, does not achieve higher event report reliability. It should be noted that for fewer number of nodes, ESRT-3x also shows improvement and achieve higher event report reliability compared to ESRT. By tuning SKE-3x ($r = 12$), it is comparable to RBC for higher number of nodes, as it can retransmit more often. This shows the usefulness of adaptation of protocol parameters. Fig. 7(b) shows that SKE-3x has the highest latency. This is obvious due to the fact that the event messages are retransmitted and almost never get lost. But again this is a tradeoff between reliability and timeliness. This also shows that (1) in worst case scenarios, when only one node is able to detect the event, the event is reported to the sink. (2) For delay tolerant applications such mechanisms are beneficial. The latency of ESRT-3x is similar to ESRT and very low, making it efficient, but less reliable compared to other protocols. Fig. 7(c) depicts the efficiency of the protocols. We observe that the RBC has a higher number of transmissions in comparison to all other protocols. One important observation about SKE-3x is that it uses comparatively fewer transmissions, as it is using one source node. Furthermore it suggests that SKE-3x require fewer retransmissions to achieve high event report reliability and is more efficient than RBC. This also shows that tuning $r = 12$ is more optimistic and SKE-3x achieves event report reliability with relatively less number of retransmissions. This study suggests that the protocol parameters are important for the performance of any DT protocol and should be tuned carefully to achieve high responsiveness.

5 Discussions

Our simulation study has quantified the certainty of the textual statement of the existing DT protocols surveys [2, 19, 20] and showed new behaviors, as we simulated a wide range of scenarios. In the light of our experimental analysis following are the main observations.

The protocols behave differently for a given application scenario and show different tradeoffs between reliability, timeliness and efficiency (Table 2). For example, hybrid protocols provide more event report reliability and timeliness but perform poor in efficiency. The ev2e protocols have good timeliness and efficiency but performs poor for event report reliability. On the other hand e2e protocols perform well with respect to event report reliability and efficiency but their timeliness is poor. Overall the hybrid protocols perform better than the e2e and ev2e protocols in terms of event report reliability and timeliness. For small scale networks and for scenarios where BEP is lower, e2e protocols outperform other approaches with respect to both efficiency and event report reliability. We also observed that existing protocols can not be deployed in harsh environments where network connectivity is transient or volatile.

	hybrid	ev2e	e2e
reliability	+	−	+
timeliness	+	+	−
efficiency	−	+	+

Table 2. Comparison of DT protocols

Our simulation study provides a generalized reference for the application designers to select an appropriate DT protocol for their specific application scenario. For example, if the targeted application is safety-critical, where the event detection is directly proportional to material or human-life danger and reliability is a major concern, then hybrid protocols with proactive routing should be selected. On the other hand if targeted application is non safety-critical, such as continues monitoring applications, where the reliability is of less concern but efficiency should be maximized, then ev2e protocols are the most suitable.

Beyond the selection of an appropriate protocol for the application scenario, our study shows that DT protocols have to cope with the dynamic and evolvable network properties. Therefore, adaptation of DT protocol parameters is needed. The number of retransmissions and number of sources per event are clearly the two adaptation criteria which can be tuned, depending on the length and reliability of the route towards the sink. Study 3 explores the opportunities for cross layer optimizations for enhancement of DT protocols. From this study it is evident that the link quality, quantified by BEP is a suitable indicator to trigger an online adaptation process. Capturing the BEP of the link (or level of congestion) at runtime and then setting the optimal number of retransmission is very promising adaptation.

6 Conclusions

We presented the first simulation based comparative study concerning the performance of data transport protocols (DT) for WSN in the context of wide range of network properties and protocol parameters. Our main result is that the existing DT protocols are specific to application scenarios and always show a tradeoff between responsiveness and efficiency. We motivated also the necessity and usefulness of the adaptation of different DT protocol parameters to the dynamic and evolvable network conditions. We are convinced that this study is an important step in understanding the performance of various classes of DT protocols and a basis for application designers to choose an appropriate protocol for their specific application scenario.

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