Multipath Virtual Sink Architecture for Wireless Sensor Networks in Harsh Environments

Winston K.G. Seah* and Hwee Pink Tan†

*Networking Department, Institute of Infocomm Research
21 Heng Mui Keng Terrace (Singapore)

†EURANDOM, P.O. Box 513, 5600 MB Eindhoven (The Netherlands)

Abstract

Wireless sensor networks are expected to be deployed in harsh environments characterized by extremely poor and fluctuating channel conditions. With the generally adopted single-sink architecture, be it static or mobile, such conditions arise due to contention near the sink as a result of multipath data delivery. The compactness of sensors with limited energy resources restricts the use of sophisticated FEC or ARQ mechanisms to improve the reliability of transmissions under such adverse conditions.

We propose a novel virtual sink architecture for wireless sensor networks that mitigates the near-sink contention by defining a group of spatially diverse physical sinks. Reliability and energy efficiency is achieved through multipath data delivery to the sinks without the need for sophisticated FEC or ARQ mechanisms. This architecture is especially suitable for indoor environments, where channel conditions are harsh due to severe multipath fading, as well as emerging applications like underwater sensor networks where the predominant physical layer is acoustic communications, which is characterized by long propagation delays and severely fluctuating link conditions. We present our proposed architecture and demonstrate its efficacy using mathematical analysis.

I. Introduction

Wireless sensor network technologies have progressed beyond research into actual deployment scenarios. Despite extensive research efforts on energy efficiency to maximize the network lifetime given the wireless communications characteristics and hardware constraints, there are always new deployment scenarios emerging with more demanding requirements, e.g. underwater sensor networks; besides, most of the scenarios that have been considered so far tend to be limited and even unrealistic. For example, how often are sensors evenly or uniformly distributed over the area of deployment? – a quintessential condition assumed in many performance studies of wireless sensor network protocols and algorithms. Wireless sensor networks are expected to be deployed in harsh environments with extremely poor channel conditions, and the compact size of sensors with limited energy resources restricts the amount of processing that can be executed on the sensors by sophisticated communications algorithms. Relay nodes have been proposed to enhance the lifetime of wireless sensor networks by serving as the local aggregation point for a cluster of sensors and also to perform in-network processing to alleviate energy depletion of the sensors [1]. However, relay nodes may become hotspots as the data from the sensors converge on them. In general, the commonly adopted single-sink architecture, be it static or mobile, is extremely vulnerable to poor channel conditions, especially when it occurs anywhere enroute to the sink, or worse, at the vicinity of the sink.

We present a multipath virtual sink network architecture using a novel approach of applying fundamental networking concepts. Multipath routing is adopted to provide alternative paths for data to be delivered in order to increase the probability of successful delivery. To minimize the chances of the multiple paths approaching one another and contending for the shared wireless channel, the paths diverge like a starburst towards multiple sinks deployed along the edges of the sensor network. These sinks collectively form the virtual sink. We validate the design by showing how simple protocols deployed in this architecture can significantly enhance the data delivery in a harsh wireless environment. Lastly, we conclude with a brief discussion on a promising new wireless sensor network application, viz., underwater sensor network, as well as ongoing research based on this architecture.

II. Network Architecture

The network topology is crucial in determining the network capacity, energy consumption, and more importantly, the reliability of the network. There must be sufficient robustness and redundancy built into the network to ensure that it continues to function even when a significant portion of the network is temporarily non-operational.

A. Virtual Sink Architecture

When the link quality is poor, the probability of successful delivery with multihop transmissions drops exponentially as the number of hops increases, and may reach an unacceptable level under harsh environments. Hence, we propose a multi-tier topology by introducing local *aggregation* points and distributing them amongst sensing nodes and multiple local sinks that are spatially apart. These aggregation points will collectively form a wireless mesh network on which data will be relayed (over fewer hops) to multiple spatially-apart local sinks, as illustrated in the LHS of Fig. 1. The ultimate goal of the wireless sensor network is to ensure that data is delivered to at least one of these sinks - hence, they collectively form a *virtual* sink.

It is assumed that these local sinks are connected via high-speed links (e.g. broadband communications links, or wired high-speed optical fibre) to a network where the resources are more than sufficient to support the communication needs of the various applications. Although we have shown a two-tier topology, the number of tiers is flexible and can be dynamically adapted to meet deployment requirements and suit environmental conditions. As the sensing coverage is very dependent on the applications' needs and the technologies used to develop the sensors, we focus only on the communication aspects of sensors such as the range and bandwidth of the communication link.

B. Multipath Data Delivery

Assuming a two-tier topology, at the lower tier, a robust multipath data delivery scheme provides end-to-end connectivity from the sensing nodes to the local aggregation points. The scheme aims to maintain *n* routes from each sensor to its neighbouring local aggregation points; the value of *n* adapts to the channel conditions as well as the criticality of the data carried in the packet. If the channel is intermittent and bandwidth is very limited, it may be better for the nodes to cache data and transmit when the channel conditions are favourable rather than attempt multiple retransmissions. For time-critical data, instead of caching, the scheme will attempt to deliver data over more routes (larger *n* value) to increase the probability of successful delivery.

Similarly, the local aggregation points form a wireless mesh network that provides multiple paths to the virtual sink. Congestion at aggregation points (mesh nodes) can occur with simultaneous arrival of high traffic volume from sensor nodes, e.g. sensor data arising from the detection of the engine noise of a moving boat on the surface in an underwater sensor network may generate a continuous burst of sensor traffic arriving at neighboring aggregation points. As the name implies, in-network data aggregation is necessary to handle the congestion at the aggregation points. Likewise, the deployment of redundant nodes (as backup aggregation points) to increase the availability of multiple disjoint paths such that backup routes are readily available can be done, where necessary. This is crucial for sending time-critical delay-intolerant data that cannot be cached until the channel conditions improve. The multipath routing protocol will select the appropriate routes from those available to achieve the required service levels.

C. Redefining multipath and retransmission

In a single-sink architecture, typical multipath routing protocols set up multiple routes between a source node and the sink node [2]. Depending on how the routes are selected, there is a strong likelihood of contention amongst intermediate relay nodes that are on different routes but close to one another. As the routes converge at the sink node, the possibility of contention is even higher. Hence, the redundancy that multipath provides in an attempt to improve packet delivery is nullified by the increased contention among nodes, which can be made worse by retransmissions.

We therefore propose that a node (e.g. A in the RHS of Fig. 1) sends a packet *simultaneously* over spatially diverse routes to multiple sinks (S_1, S_2, $\cdots$, S_M), which form the virtual sink. As long as a copy of the packet reaches one of these sinks, delivery is successful. This can be considered as retransmitting a packet simultaneously instead of sequentially (as in simple Stop-and-wait Automatic Repeat Request (ARQ)), and this may result in lower latency and fewer packet transmissions, thus saving energy, under certain channel conditions. The use of spatially diverse paths also reduces the possibility of inter-path contention.

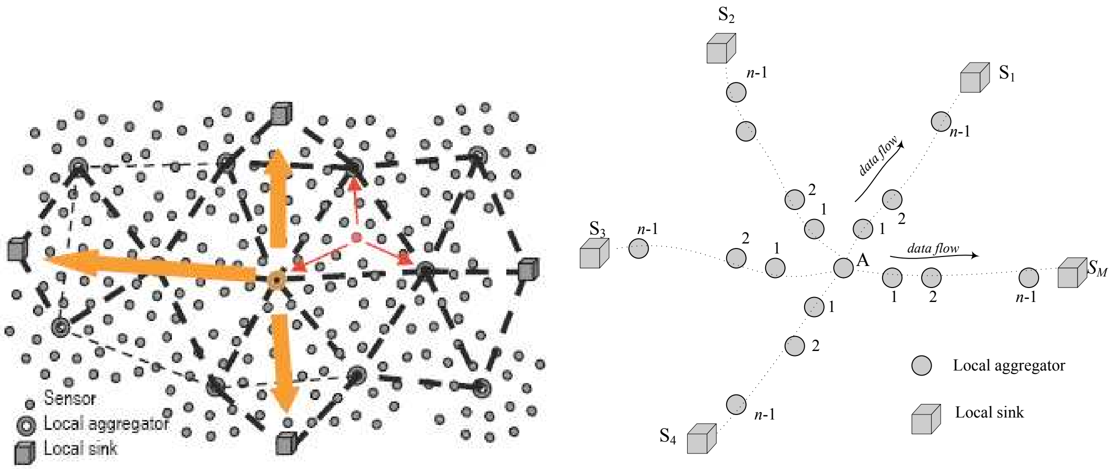

Fig. 1. Virtual Sink Architecture (left) and Multipath routing over spatially-diverse paths (right).

III. Analysis: Spatially diverse Multipath Routing vs Single path routing with retransmissions

For the proposed virtual sink architecture, we consider the delivery of a single data packet from each local aggregator to local sinks and analyze the performance of multi-hop routing in terms of latency, transmission reliability and energy consumption, which are important metrics for data dissemination in wireless sensor networks.

Let us consider a source node (local aggregator) for which *M* spatially-diverse paths to *M* local sinks are available, where each path *i* comprises *n* equally-spaced hops. We assume that *M* is small, so that the paths are sufficiently diverse spatially, and therefore the transmissions along each path do not interfere with those of other paths. We associate a parameter $p_i(j)$ for each path *i* to denote the probability of transmission failure over the j^{th} hop, and assume that $p_i(j)$, $1 \leq j \leq n$, are independent. This model is illustrated in the RHS of Fig. 1.

Let *t* denote the total number of transmission attempts. Assuming all hops to be equidistant with a propagation delay of τ_p and the transmission power is fixed, the energy consumed for the transmission of each packet is proportional to *t*. If τ_x denotes the time required for a packet to be delivered per hop, then $\tau_x = \tau_t + \tau_p$, where τ_t is the transmission time required for each packet.

A. Spatially-diverse Multi-path Routing

With this approach, the local aggregator sends the packet simultaneously over all *M* paths. Along each path *i*, the packet reaches the corresponding local sink only if transmissions over all *n* hops are successful. As long as a copy of the packet reaches one of the local sinks, delivery is successful.

Let us consider the transmission of a single packet over path *i*. If t_i denotes the total number of transmissions after the first hop, where $0 \leq t_i \leq n$-1, then we have the following pmf:

$$P(t_i = t) \quad = \quad \begin{cases} p_i(t+1)\prod_{j=1}^{t}(1-p_i(j)), & t < n-1; \\ \prod_{j=1}^{t}(1-p_i(j)), & t = n-1. \end{cases}$$

If t_{MP} denotes the *expected* total number of transmissions for a single packet, then we have:

$$t_{MP} = 1 + \sum_{i=1}^{M}\sum_{t=0}^{n-1} tP(t_i = t), \qquad (1)$$

where the first term corresponds to the transmission that occurs at the local aggregator, and the second term denotes the subsequent transmissions along each path.

Along any path *i*, the packet will be successfully received only if transmissions over *all* *n* hops are successful, and this occurs with the following probability:

$$P_i = \prod_{j=1}^{n}(1 - p_i(j)),$$

since $p_i(j)$, 1≤ $j \leq n$, are independent.

Hence, the probability that none of the *M* copies arrives at the local sinks is $\prod_{i=1}^{M}$(1 - P_i), since the channel behavior over different paths are assumed to be independent. Therefore, the probability of successful packet delivery (which measures the reliability of the routing mechanism) is given by:

$$P_{MP} = 1 - \prod_{i=1}^{M}(1 - P_i). \tag{2}$$

Conditioned on successful delivery, the total packet delay (or latency), T_{MP}, is given as follows:

$$T_{MP} = n\tau_x, \tag{3}$$

since each packet must traverse *n* hops before arriving at the local sink.

B. Single-path routing with Stop-and-Wait ARQ

With this approach, the aggregator selects *one* of the *M* paths (e.g., path *i*) to send the packet to the corresponding sink. When a transmission over any hop along the path fails, a simple Stop-and-Wait ARQ strategy is used for re-transmission over that hop.

Consider the packet transmission from node A to node B over a single hop. When node B receives the packet from node A, it sends an acknowledgement (ACK) packet to node A, and proceeds to forward the packet to the node along the next hop. If node A does not receive an acknowledgement packet from node B after a time-out interval, τ_o, it assumes that packet transmission has failed, and initiates a re-transmission.

Let us assume that there are $r_i(j)$ transmission failures (or re-transmissions) over hop *j*, $r_i(j) \geq$ 0, such that r_i = $\sum_{j=1}^{n} r_i(j)$ is the total number of retransmissions. In this case, the total number of transmissions, t_{SP,r_i}, (including data and ACK packets) is given by:

$$t_{SP,r_i} = 2n + r_i \tag{4}$$

Then, we have the following:

$$P(t_{SP,r_i} = 2n + r_i) = \sum_{\sum_{j=1}^{n} r_i(j)=r_i, r_i(j)\geq 0} \prod_{j=1}^{n} p_i(j)^{r_i(j)}(1 - p_i(j)).$$

For the special case where $p_i(j)$=p_i, the pmf of t_{SP,r_i} reduces to a *negative binomial* distribution, given as follows:

$$P(t_{SP,r_i} = 2n + r_i) = \binom{n-1+r_i}{n-1} p_i^{r_i}(1-p_i)^n.$$

Assuming that, due to energy constraints, a maximum of *R* retransmissions are permitted, the probability of successful packet delivery is given as follows:

$$P_{SP,R} = \sum_{r_i=0}^{R} P(t_{SP,r_i} = 2n + r_i).$$

If r_i retransmissions occur before the packet is successfully delivered, then the total packet delay is T_{SP,r_i} = $r_i\tau_o$ + $n\tau_x$. Hence, conditioned on successful delivery within *R* retransmissions, we have the following:

$$P(T_{SP,r_i} = r_i\tau_o + n\tau_x) = \frac{P(t_{SP} = 2n + r_i)}{P_{SP,R}} \tag{5}$$

Therefore, the conditional *expected* packet delay, $T_{SP,R}$, is given as follows:

$$\begin{aligned} T_{SP,R} &= n\tau_x + \tau_o \sum_{r_i=0}^{R} \frac{r_i P(t_{SP} = 2n + r_i)}{P_{SP,R}} \\ &= T_{MP} + \tau_o \sum_{r_i=0}^{R} \frac{r_i P(t_{SP} = 2n + r_i)}{P_{SP,R}} \end{aligned}$$

Hence, conditioned on packet delivery being successful, the latency introduced by single-path routing with ARQ is always *larger* than the multi-path routing protocol as long as retransmissions are permitted.

C. Numerical results

In this section, we compare the performance of both routing mechanisms in terms of numerical results computed using Eq. (1) - (5).

1) Energy constraint: We consider the scenario where the bottleneck is the energy constraint of each node. For this scenario, we evaluate the reliability and latency, assuming that both routing mechanisms have *equal* energy consumption. This is done by setting the maximum allowable number of retransmissions, *R*, such that $t_{SP,R}$ = t_{MP}, i.e., we have the following:

$$2n + R = 1 + \sum_{i=1}^{M} \sum_{t=0}^{n-1} tP(t_i = t). \quad (6)$$

We begin with the simplest case where the channel is *spatially-invariant*, and is characterized by a single parameter, *p*, i.e., $p_i(j)$ = *p* ∀ *i*,*j*. We plot P_{MP} and $P_{SP,R}$ (with *R* computed using Eq. (6)) as a function of *p* for *M*=4, *n*={5,10,15} and *n*=10, *M*={4,5,6} in Fig. 2. We also plot the corresponding degradation in latency, conditioned on successful packet delivery, as a factor of τ_o, of the single-path algorithm in Fig. 3.

For a given value of *M* and *n*, the SP protocol is more reliable (at the expense of high latency) than the MP protocol when the channel is very good. However, there exists a threshold, $p_{thres,r}$, such that for $p > p_{thres,r}$, the MP protocol becomes more reliable while maintaining lower or the same latency compared to the SP protocol. In terms of latency, there exists a threshold, $p_{thres,l}$, such that when $p < p_{thres,l}$, the SP protocol always incurs additional latency compared to the MP protocol; however, for $p > p_{thres,l}$, both protocols incur the same latency.

For a fixed *M*, as *n* increases, we observe that both $p_{thres,r}$ and $p_{thres,l}$ are reduced. This implies that a larger region (in terms of *p*) of performance gain achieved by the MP protocol in terms of reliability is traded off with a smaller region of performance gain in terms of latency as the hop-count is increased.

On the other hand, for a given *n*, as *M* increases, we observe that both $p_{thres,r}$ and $p_{thres,l}$ are increased. This implies that a smaller region of performance again achieved by the MP protocol in terms of reliability is traded off with a larger region of performance gain in terms of latency as the number of routing paths is increased.

Next, we introduce *spatial-variance* in the channel over the M paths, while maintaining the invariance over the *n* hops of each path, i.e., $p_i(j)$=p_i ∀ *i*,*j*, $p_i \neq p_k$, $i \neq k$. We investigate the impact of this spatial-variance on the reliability and latency of each protocol, which maintaining the same level of energy consumption. For *M* = 5, *n* = 10, and $\overline{p}$={0.1,0.11,$\cdots$,0.2}, we compare P_{MP} and $P_{SP,R}$ as a function of the channel for two cases (i) spatially-invariant channel with p_i = $\overline{p}$ and (ii) spatially-variant channel with p_i = $\overline{p}$+0.01(*i*-3), and the results are shown in the LHS of Fig. 4. The corresponding results comparing the latency are shown in the RHS of Fig. 4. We note that the the *average* probability of transmission failure over all paths in both cases are the same and given by $\overline{p}$.

We observe that spatial-variance in the channel improves the reliability of each protocol, where the improvement is more significant for the multi-path protocol. However, the improvement in reliability for the single-path protocol is achieved at the expense of increased latency.

2) Reliability constraint: Next, we consider the scenario where the data packet is loss-sensitive, and hence, reliability becomes the most important criteria. For this scenario, we evaluate the energy consumption and latency, assuming that both routing mechanisms have *equal* reliability. This is done by setting the maximum allowable number of retransmissions, *R*, such that $|P_{MP}$ - $P_{SP,R}|$ is minimized.

We consider the case where the channel is *spatially-invariant*, and is characterized by a single parameter, *p*, i.e., $p_i(j)$ = *p* ∀ *i*,*j*. We plot t_{MP} and t_{SP} as a function of *p* for *M*=4, *n*={5,10,15} and *n*=10, *M*={3,4,5} in Fig. 5. We also plot the corresponding degradation in latency, conditioned on successful packet delivery, as a factor of τ_o, of the single-path algorithm in Fig. 6.

For a given value of *M* and *n*, the SP protocol is more energy-efficient than the MP protocol when the channel is very good. However, there exists a threshold, $p_{thres,r}$, such that for $p > p_{thres,r}$, the MP protocol becomes more energy-efficient. In terms of latency, the SP protocol always incurs additional latency compared to the MP protocol.

For a fixed *M*, as *n* increases, we observe that $p_{thres,r}$ is reduced. This implies that a larger region (in terms of *p*) of performance gain is achieved by the MP protocol in terms of energy-efficiency as the hop-count is increased. On the other hand, for a given *n*, as *M* increases, we observe that $p_{thres,r}$ is increased. This implies that a smaller region of performance again is achieved by the MP protocol in terms of energy-efficiency as the number of routing paths is increased.

Next, we investigate the impact of this spatial-variance on the reliability and latency of each protocol, which maintaining the same level of energy consumption. For *M* = 5, *n* = 10, and $\overline{p}$={0.1,0.11,$\cdots$,0.2}, we compare t_{MP} and t_{SP} as a function of the channel for two cases (i) spatially-invariant channel with p_i = $\overline{p}$ and (ii) spatially-variant channel with p_i = $\overline{p}$+0.01(*i*-3), and the results are shown in the LHS of Fig. 7. The corresponding results comparing the latency are shown in the RHS of Fig. 7.

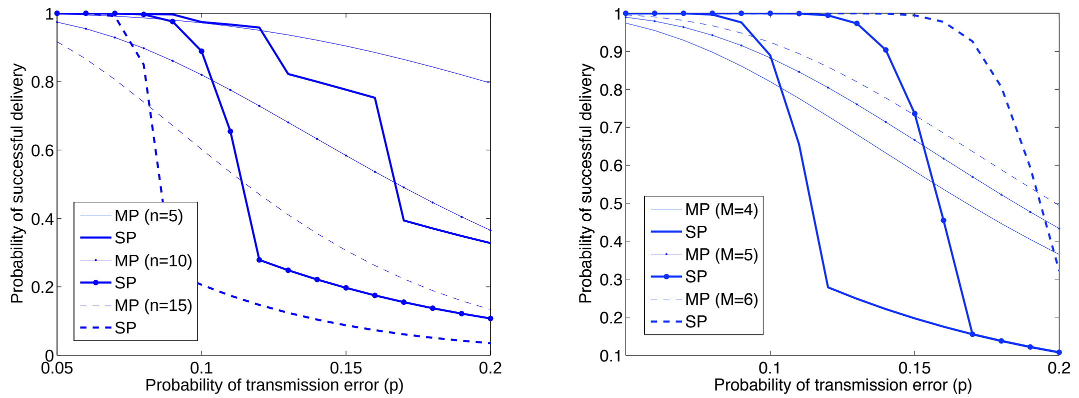

Fig. 2. Probability of successful packet delivery vs channel quality for each routing mechanism for M=4, n={5,10,15} (left) and n=10, M={4,5,6} (right).

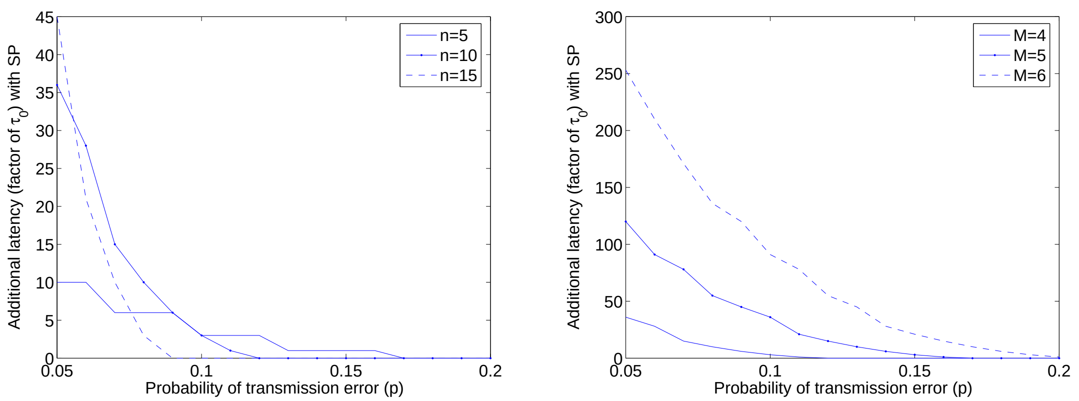

Fig. 3. Degradation of latency (factor of τ_o) of single-path algorithm vs channel quality for M=4, n={5,10,15} (left) and n=10, M={4,5,6} (right).

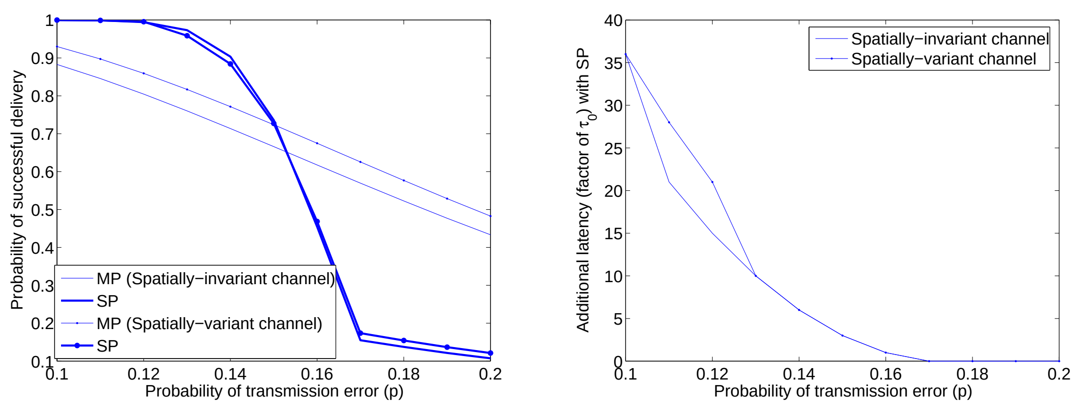

Fig. 4. Impact of spatial-variance of channel on the probability of successful packet delivery (left) and degradation of latency (factor of τ_o) of SP algorithm (right) vs channel quality for M=5, n=10.

We observe that spatial-variance in the channel reduces the region of performance gain achieved by the MP protocol in terms of energy-efficiency.

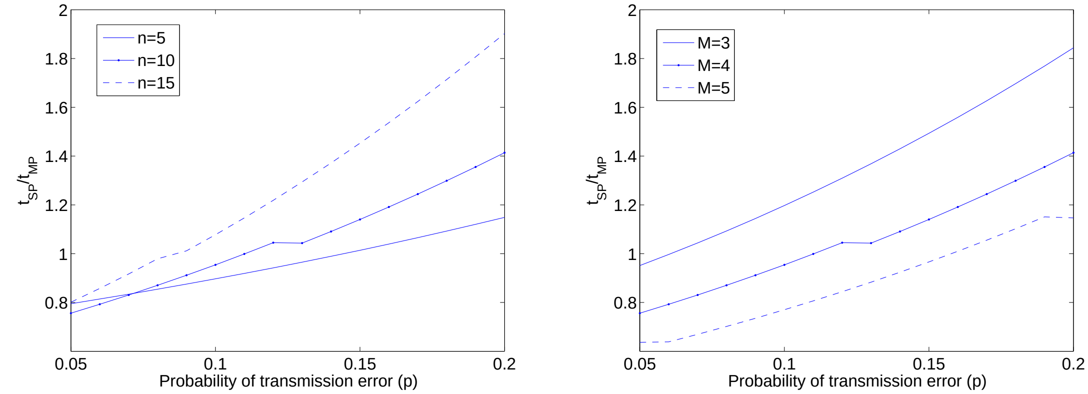

Fig. 5. Energy consumption vs channel quality for each routing mechanism for M=4, n={5,10,15} (left) and n=10, M={3,4,5} (right).

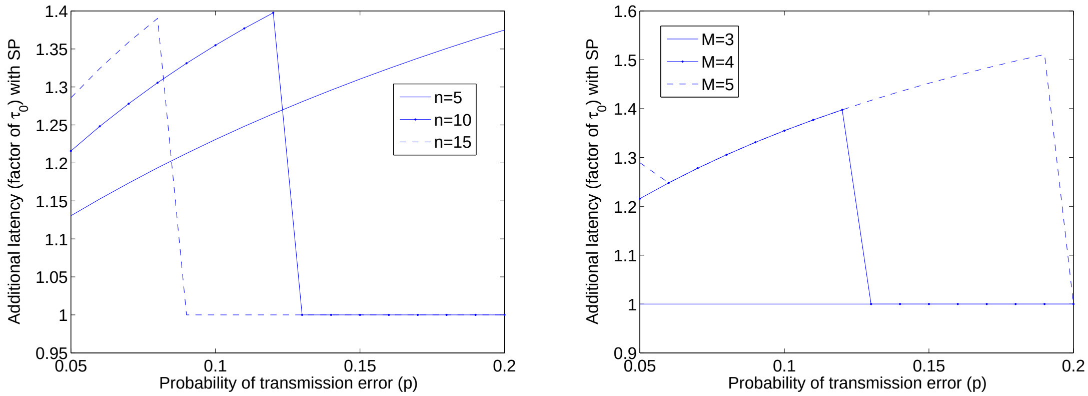

Fig. 6. Degradation of latency (factor of τ_o) of single-path algorithm vs channel quality for M=4, n={5,10,15} (left) and n=10, M={3,4,5} (right).

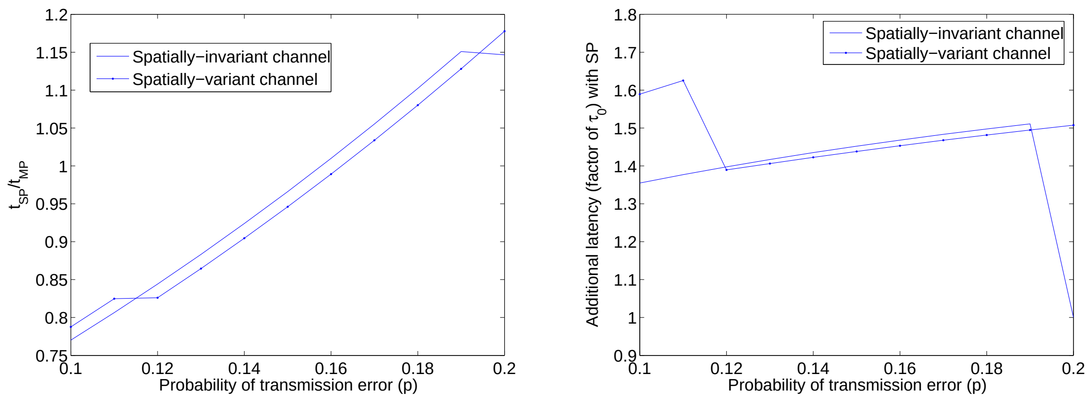

Fig. 7. Impact of spatial-variance of channel on the energy consumption (left) and degradation of latency (factor of τ_o) of SP algorithm (right) vs channel quality for M=5, n=10.

IV. Application Scenario

Potential applications for wireless sensor networks have emerged in underwater scenarios. Many applications have been envisaged for underwater sensor networks, including seismic monitoring, equipment monitoring and fault detection, and support for swarms of underwater autonomous vehicles. One particular application that presents strong economic benefits for using underwater sensor networks over conventional methods is the seismic monitoring of undersea oilfields. To date, seismic monitoring is mostly carried out by a ship towing a large array of hydrophones on the ocean surface - a method which is both costly as well as operationally intensive [3].

Terrestrial sensor networks are typically made up of a large number of small low-cost sensor nodes communicating over short ranges using radio frequency (RF) transmissions. On the other hand, underwater sensor networks are likely to be much less dense in numbers as the nodes are comparatively much more expensive and difficult to deploy. Hence, we do not have the advantages of reliability and redundancy from numbers like in terrestrial sensor networks. Another significant difference is the transmission method used for underwater wireless communications. RF or radio wave propagation suffers from severe attenuation in water and has been successfully done only at very low frequencies, involving large antenna and high transmission power. Hence, the current viable underwater physical layer technology is acoustic communications. The salient features of acoustic communications render many schemes that have been designed for RF-based terrestrial sensor networks unusable. Besides having low bandwidth and a propagation delay five orders of magnitude higher than RF in air, the link quality also poses many difficulties [4]. Underwater link quality is extremely volatile, suffering frequent temporal disconnections due to numerous reasons like, underwater current, temperature fluctuation, severe multipath fading, ambient noise and interference from marine life.

The high propagation delay makes it extremely inefficient to use ARQ techniques that are commonly used in terrestrial networks for packet loss detection, and error recovery methods like retransmission incur excessive latency and signaling overheads. It would then appear that forward error correction (FEC) techniques can be applied to provide robustness against errors but at the cost of additional redundant bits competing for the already scarce bandwidth, and the processing needed for encoding and decoding further drains the critical energy resources.

From the results presented in Section III-C, for a given topology, the multipath approach always incurs lower latency, and is more reliable and energy efficient when the channel becomes harsh, e.g., when the probability of transmission loss goes beyond 10%. This is extremely beneficial for environments with high propagation delay – underwater acoustic communications being a good example. Furthermore, loss ratios of more than 10% is not uncommon in terrestrial environments [5] and can be much worse in underwater scenarios [4]. Our analysis also shows that the region of performance gain for the multipath protocol becomes larger with fewer paths of higher hop count and when the channel is spatially variant. These analytical results further strengthen preliminary findings on applying this architecture in underwater sensor networks [6].

V. Conclusion and Future Work

Despite immense research efforts on wireless sensor networks, many new applications are emerging which put increasingly stringent requirements on the technology. The harsh environments in which wireless sensor networks are expected to be deployed also pose significant challenges to the communication schemes used to transport the data from the sensors to the sinks. As an alternative to the commonly adopted single-sink architecture, which is extremely vulnerable to poor channel conditions, we have proposed a novel multipath virtual sink architecture and demonstrated its efficiency analytically. As our ongoing work, we are studying how the different parameters such as the number of multiple paths to use can be dynamically adjusted according to the channel conditions, in order to minimize unnecessary transmissions (thus improving energy efficiency) while maintaining reliability of data delivery.

References

[1] T.Y. Hou, Y. Shi, H.D. Sherali and S.F. Midkiff, “On Energy Provisioning and Relay Node Placement for Wireless Sensor Networks”, IEEE Transactions on Wireless Communications, 4(5):2579-2590, Sep 2005.

[2] S. Mueller, R. P. Tsang, and D. Ghosal, “Multipath Routing in Mobile Ad Hoc Networks: Issues and Challenges”, M.C. Calzarossa and E. Gelenbe (Eds.): MASCOTS 2003, LNCS 2965, pp. 209-234, 2004. Springer-Verlag Berlin Heidelberg 2004.

[3] W. Lynn, “3-D, 4-D and Beyond”, Proceedings of the Offshore Technology Conference, Houston, Texas, USA, 5–8 May, 1997.

[4] E.M. Sozer, M. Stojanovic and J.G. Proakis, “Underwater Acoustic Networks”, IEEE Journal of Oceanic Engineering, 25(1):72-83, Jan 2000.

[5] J. Zhao and R. Govindan, “Understanding packet delivery performance in dense wireless sensor networks”, Proceedings of ACM Sensys 2003, Los Angeles, California, USA, 2003.

[6] W.K.G. Seah, “Multipath Virtual Sink Architecture for Underwater Sensor Networks”, Proceedings of the OCEANS 2006 Asia Pacific Conference, Singapore, 16–19 May, 2006.