Transplanting Protocols Across Different Environments

TAEWOO KWON, EMRE ERTIN, ANISH ARORA

Technical Report
OSU-CISRC-9/08-TR47

Transplanting Protocols Across Different Environments *

Taewoo Kwon, Emre Ertin, Anish Arora
The Ohio State University,
Columbus, OH 43210
{kwonta, ertine, anish}@cse.ohio-state.edu

Abstract

In this paper, we consider the basic problem of transplanting a protocol from one network to another network that may have different signal propagation characteristics and inter-node spacing. To achieve predictable protocol behavior in the target network, we exploit the concept of "link usage spectrum" and seek to reproduce the spectrum of the source network as closely as is possible in the target network. The link usage spectrum depends upon the protocol in question; we illustrate for a family of protocols how the link usage spectrum is calculated analytically from the protocol metric for choosing forwarding links in the network. We also illustrate our technique for achieving comparable protocol behavior via experiments and simulations with a well known protocol in indoor and outdoor network settings.

Keywords: Wireless Sensor Network,Testbed, Planning, Calibration

1 Introduction

Experiences in deploying low-power wireless networks during this decade have yielded a number of surprises, wherein network behavior in the field diverged substantially from that seen in laboratory tests. A combination of factors has contributed to these surprises. One key factor is that the effective topology of the laboratory tests is different from that of the field deployment: Not only is inter-node spatial (separation) scale different in the two networks, but the environment signal propagation characteristics also tend to be different, and as a result the link selections and the intra-node traffic interference diverge. Differences in externally induced communication interference are another factor. Other scale differences in the field deployment, i.e., increasing the number of the nodes fielded, and consequent phase transition or instability issues are yet another factor. Moreover, network protocol behaviors can themselves exhibit nontrivial variability, and this variability may only be inadequately understood in the testing phase.

The multi-faceted difficulty with ensuring desired protocol behavior in the field, coupled with the high cost of testing and tuning the performance in the field, motivates the scientific study of tools and techniques that simplify predictability of network behavior. In this paper, we take a step towards addressing this difficulty by focusing on the first of these factors, i.e., achieving predictable performance in spite of changes in the effective topology that result from changing the environment of the network and adjusting the internode scaling. We limit our attention to this factor not just because it is a key factor based on experience, but also because a separation of concerns is desirable (as well as feasible) with respect to the other factors.

What do we mean by predictable performance? Even if the test and deployment environments are the same and we only adjust the intra-node spatial scale of the network in going from one network to the other, realizing identical protocol behavior in two different networks is hard (albeit not impossible). In several cases, it is however both sufficient and feasible to realize a probabilistic equivalence between two such networks. By probabilistic equivalence, we informally mean that the set of links for the two networks are sampled from the same multivariate Gaussian probability distribution.

For two networks at different spatial scales in the same environment, positive results for achieving probabilistic equivalence have been presented earlier, i.e., by using transmission power control [1]. (The power control may be realized via attenuator hardware and/or software control.) That study also experimentally compared the performance metrics of two wireless sensor network (WSN) protocols —Sprinkler [2],

*This work was supported in part by NSF grants No. 0520222 and 0341703

a protocol that provides a bulk data transmission service, and LOF [3], a protocol that provides a beacon-free routing service— at different spatial scales in Kansei, an indoor WSN testbed [4], to illustrate how to select the transmission power to achieve probabilistic equivalent behavior when scaling all inter-node distances by some constant.

In contrast, for two networks at different spatial scales in different environments —in particular, with different path loss exponents— it is straightforward to show that it is impossible to achieve probabilistic equivalence using only transmission power control. This necessitates consideration of alternative techniques.

Link Usage Spectrum. In this paper, towards achieving comparable performance in networks in potentially different environments, we adopt the concept of realizing the same (or close to the same same) "link usage spectrum" in the networks. Informally speaking, the link usage spectrum of a network is the probability distribution with which the network protocol selects links of different length from among all the available links in the network at hand. Thus, even if the "available" link spectrum of two networks are different but the probability distribution of the chosen links are comparable, the protocol behavior of the two will likely be comparable.

By way of illustration of how the link usage spectrum is used in achieving predictable network behavior, we consider the case where a prototype network is tested in an indoor environment before it is fielded somewhere outside. Since the indoor environment is persistent and easily instrumented for tests, it is relatively easy to collect fine-grain, long running protocol behavior information in it. Thus, if one could efficiently collect/determine link usage spectrum data for the outdoor deployment environment, then one could (analytically or experimentally) design the link usage spectrum for the indoor tests (say by choosing the indoor network spatial scaling facto and transmission power level) to be close to that of the field network, The resulting observed indoor protocol behavior would be predictive of the behavior to be observed in the field.

There are two major factors that affect the link usage spectrum: the metric of chosen by the network protocol for forwarding traffic and, more generically the signal to noise ratio (SNR), or RSSI, values of links. It is often the case that the metric itself involves a function of the SNR (or RSSI) as well as the distance traversed by the link. In these cases, the link usage spectrum can be reformulated as a function of relative preference based on SNR and forwarding distance. We emphasize that this is only one of the ways to reformulate the link usage spectrum, and that the analysis we perform subsequently in the paper is readily adapted to several other routing metrics.

There has been little previous work on the link usage spectrum. There is significant literature however, e.g. [5], that models the bit error rate for radio channels and thus calculates performance metrics such as signal to noise ratio (SNR), packet reliability rate (PRR), expected number of transmissions (ETX), PRR $\times$ d (the forwarding distance) [6], and expected latency per unit distance (ELD=$\frac{1}{\mathrm{PRR}\times\mathrm{d}}$) [3]. A related work that implicitly exploits the link usage spectrum idea is [6], although its role is different: the spectrum is used as a tool for calculating average network metrics that are in turn used for choosing between protocols and optimizing a protocol realization with respect to its intended forwarding metric. [6] also uses numerical simulations for calculating the spectrum; by way of contrast, we provide a closed form equation for expressing the link usage spectrum in the context of the forwarding metric at hand.

Contributions. Our main contribution is proposing a general technique for achieving predictable performance in different networks based on the link usage spectrum concept. Specifically, we define a metric, the XPlantError, which is the l_1 distance between the link usage spectrum of the two networks, and minimize the XPlantError between the test and deployment networks.

We illustrate how the link usage spectrum is analytically derived for network protocols whose forwarding metric depends on Packet Reliability Rate (PRR), distance, and other variables based on SNR. We further show that the analytic expression is corroborated by experimental measurements and simulation of the link usage spectrum in such contexts. Also, we perform indoor and outdoor experiments with a messaging protocol, the Collection Tree Protocol (CTP) [8] (which is distributed with the TinyOS 2.0 release) corroborate the validity of the XPlantError approach for achieving comparable network behavior.

Road map. In Section 2, we define link usage spectrum, XPlantError, and illustrate how to analytically calculate the link usage spectrum for one class of network protocols. In Section 3, we provide an experimental and simulation study of CTP protocol transplantation in the context of a simple chain topology in indoor and outdoor networks. In Section 4, we discuss variations of the definition of XPlantError for achieving potentially higher fidelity in predicting network behavior, as well as limitations of our formulation of link usage. In Section 5, we summarize our observations and discuss future work.

2 Link Usage Spectrum and Network Transplant Error

Wireless network behavior is largely influenced by the performance of the wireless links between the nodes of the network. Performance of a wireless link between a transmitter and receiver is determined by the RF channel between the terminals (environment model) and the bit-error-performance of their wireless transceivers (radio model). RF channel models describe the probabilistic relation between link distance and path loss. Specifically, in any given network links of same length experience different channel realizations due to spatial variations in obstructions and reflectors in the scene. As a result, the received signal strength experienced on links of length d is a random variable $R(d)$. The RF channel model induces a distribution on $R(d)$. As an example, log-normal shadowing model, a large scale fading model employed commonly in indoor and outdoor link studies, described the received signal strength as:

$$R(d) = P_t - PL(d_0) - 10\eta \log(d/d_0) + N_\sigma \qquad (1)$$

where η is the path loss exponent, P_t is the transmitter power, and $PL(d_0)$ is the path loss observed at distance d_0 in dB and N_σ is a zero-mean Gaussian random variable with standard deviation σ, representing spatial variations in the RF environment. The received signal to noise ratio(SNR) at the receiver $y(d)$ is given by the received signal power $R(d)$ reduced by the noise power P_0.

$$y(d) = R(d) - P_0 \text{ (in dB)} \qquad (2)$$

The radio receiver performance can be characterized by representing the packet reception rate PRR(y) as a function the received signal to noise ratio y. PRR(y) gives the probability that a packet received with SNR of y will be decoded correctly by the receiver. The relation between packet-reception-rate and SNR depends on the modulation scheme and the packet encoding scheme employed by the radio transceiver. The function PRR(y) is a monotonously increasing function with range $[0, 1]$ and acts as a soft limiter. The PRR(y) function for the 802.15.4 wireless physical layer is given in Figure 1. The combination of the environment and radio model can completely describe the link properties observed in a wireless network for low-rate/time division access where the interference is not significant. Experimental [13] and Analytical [5] studies of low power wireless links have shown that high percentage of network links will be either good or bad ($< 10\%$ and $> 90\%$ PRR).

We note that the reported link reliability statistics by previous studies are based on the *a priori* distribution of the link realizations. If we consider *posterior* distribution of the selected links for a network protocol will be even more skewed towards high PRR values. As a result network forwarding performance is grossly determined by the link lengths that are being utilized and less so by the small variations in link qualities. Therefore, in this paper we focus on a particular network statistics called link usage spectrum: the probability distribution with which a given network protocol selects links of different length from among all the available links in the network at hand.

Specifically, consider a wireless network $\mathcal{W} = (\{l_j\}, \eta, \sigma)$ with link set $\{l_j\}_{j=1}^M$ and the RF environment (η, σ) employing a network protocol $\mathcal{P}$. We note $\mathcal{W}$ is a probabilistic object, referring to the ensemble of link set realizations. For each realization of the wireless network $\mathcal{W}$, network protocol $\mathcal{P}$ chooses a subset of the link set for forwarding of data. We consider one dimensional linear networks with uniform node spacing, where the link lengths $d_j \equiv d(l_j)$ are constrained to the finite set $\{\tau, 2\tau, 3\tau, \ldots, N\tau\}$, where τ is the minimum node spacing. The link usage spectrum $L(\mathcal{W}, \mathcal{P}, i)$ is the discrete probability distribution over the length of links induced by the network protocol $\mathcal{P}$.

$$L(\mathcal{W}, \mathcal{P}, i) = \text{Prob}[d(l) = i\tau] \qquad (3)$$

The link usage spectrum is a universal summary statistics of network behavior. The fundamental importance of link usage spectrum stems from the fact that many network wide metrics can be calculated as averages over link realizations weighted by the usage spectrum as discussed in Section 5. As a result, we propose to use the link usage spectrum to match protocol behavior across scales and environments. The link usage spectrum can be calculated *in situ* empirically as averages over node link usages or can be derived directly from RF environment and physical layer models. In this paper, we derive analytical expressions for link usage spectrum for the ELD forwarding protocol that maximizes PRR×d under lognormal shadowing model. While the theorems are presented using the ELD protocol metric of evaulating links, they can be easily customized to other forwarding protocols based on optimization of network metrics encapsulating PRR and d.

Theorem 1. *For a protocol $\mathcal{P}$ which uses PRR × d as the metric for choosing forwarding links, the probability of choosing link l_i over link l_j can be expressed as below:*

$$P(PRR(y_i) * d_i > PRR(y_j) * d_j)$$

$$= \int_{-\infty}^{a} \frac{1}{\sigma\sqrt{2\pi}} \left(\frac{1}{2} + \frac{1}{\sqrt{\pi}}\left(z - \frac{z^3}{3} + ...\right)\right) e^{-\frac{(y_i-\mu_{y_i})^2}{2\sigma^2}} dy_i$$

$$+ \int_{a}^{\infty} \frac{1}{\sigma\sqrt{2\pi}} \left(\frac{1}{2} + \frac{1}{2} erf\left(\frac{g(\beta_j) - \mu_{y_j}}{\sqrt{2}\sigma}\right)\right) e^{-\frac{(y_i-\mu_{y_i})^2}{2\sigma^2}} dy_i$$

, where $z = \frac{y_i - \mu_{y_j}}{\sigma\sqrt{2}}$, and y_i, y_j are SNR (dB) values of link l_i, l_j, and d_i, d_j are link lengths of link l_i, l_j, and $g(\beta_j) = a$ if $\beta_j (= \frac{d_j}{d_i}) \geq 1$, $g(\beta_j) = \infty$ if $\beta_j < 1$

Proof. The probability of choosing l_i over l_j with metric $PRR \times D$,

$$P(PRR(y_i) * d_i > PRR(y_j) * d_j)$$

$$= P\left(PRR(y_i) > \frac{d_j}{d_i} PRR(y_j)\right)$$

Let's set $\frac{d_j}{d_i} = \beta_j$.

$$= P\left(PRR(y_i) > \beta_j PRR(y_j)\right)$$

Here we approximate

$$PRR(y_i) > \beta_j PRR(y_j) \approxeq y_i > h(y_j)$$

, where

$$h(y_j) = \begin{cases} y_j, & \text{if } y_j < a \\ a, & \text{if } y_j \geq a \end{cases}$$

, when $a = PRR^{-1}(\beta_j)$ if $\beta_j < 1$

Applying the above approximation.

When $\beta_j < 1$:

$$P\left(PRR(y_i) > \beta_j PRR(y_j)\right)$$

$$= P(y_i > y_j, y_j < a) + P(y_i \geq a, y_j \geq a)$$

$$= P(y_i > y_j, y_i < a) + P(y_i \geq a)$$

Because y_i, y_j are gaussian,

$$= \int_{-\infty}^{a} \int_{-\infty}^{y_i} \frac{1}{2\pi\sigma^2} e^{-\frac{(y_i-\mu_{y_i})^2 + (y_j-\mu_{y_j})^2}{2\sigma^2}} dy_j dy_i$$

$$+ \int_{a}^{\infty} \int_{-\infty}^{\infty} \frac{1}{2\pi\sigma^2} e^{-\frac{(y_i-\mu_{y_i})^2 + (y_j-\mu_{y_j})^2}{2\sigma^2}} dy_j dy_i$$

When $\beta_j \geq 1$:

$$P\left(PRR(y_i) > \beta_j PRR(y_j)\right)$$

$$= 1 - P\left(PRR(y_j) > \frac{1}{\beta_j} PRR(y_i)\right)$$

$$= 1 - \left(P(y_j > y_i, y_i < a) + P(y_j \geq a, y_i \geq a)\right)$$

, where $a = PRR^{-1}(\frac{1}{\beta_j})$

$$= 1 - \left(P(y_j > y_i, y_j < a) + P(y_j \geq a)\right)$$

$$= P(y_i > y_j, y_i < a) + P(y_j \leq a, y_i \geq a)$$

$$= \int_{-\infty}^{a} \int_{-\infty}^{y_i} \frac{1}{2\pi\sigma^2} e^{-\frac{(y_i-\mu_{y_i})^2 + (y_j-\mu_{y_j})^2}{2\sigma^2}} dy_j dy_i$$

$$+ \int_{a}^{\infty} \int_{-\infty}^{a} \frac{1}{2\pi\sigma^2} e^{-\frac{(y_i-\mu_{y_i})^2 + (y_j-\mu_{y_j})^2}{2\sigma^2}} dy_j dy_i$$

By combining two cases,

$$P\left(PRR(y_i) > \beta_j PRR(y_j)\right)$$

$$= \int_{-\infty}^{a} \frac{1}{\sigma\sqrt{2\pi}} \left(\frac{1}{2} + \frac{1}{2} erf\left(\frac{y_i - \mu_{y_j}}{\sigma\sqrt{2}}\right)\right) e^{-\frac{(y_i-\mu_{y_i})^2}{2\sigma^2}} dy_i$$

$$+ \int_{a}^{\infty} \frac{1}{\sigma\sqrt{2\pi}} \left(\frac{1}{2} + \frac{1}{2} erf\left(\frac{g(\beta_j) - \mu_{y_j}}{\sqrt{2}\sigma}\right)\right) e^{-\frac{(y_i-\mu_{y_i})^2}{2\sigma^2}} dy_i$$

,where

$$g(\beta_j) = \begin{cases} a, & \text{if } \beta_j \geq 1 \\ \infty, & \text{if } \beta_j < 1 \end{cases}$$

Here, erf(z) can be approximated with the taylor series

$erf(z) = \frac{2}{\sqrt{\pi}} \sum_{n=0}^{\infty} \frac{(-1)^n z^{2n+1}}{n!(2n+1)}$
$= \frac{2}{\sqrt{\pi}} \left(z - \frac{z^3}{3} + \frac{z^5}{10} - \frac{z^7}{42} + \frac{z^9}{216} - ...\right)$

Finally,

$$= \int_{-\infty}^{a} \frac{1}{\sigma\sqrt{2\pi}} \left(\frac{1}{2} + \frac{1}{\sqrt{\pi}}\left(z - \frac{z^3}{3} + ...\right)\right) e^{-\frac{(y_i-\mu_{y_i})^2}{2\sigma^2}} dy_i$$

$$+\int_{a}^{\infty}\frac{1}{\sigma\sqrt{2\pi}}\left(\frac{1}{2}+\frac{1}{2}erf\left(\frac{g(\beta_j)-\mu_{y_j}}{\sqrt{2}\sigma}\right)\right)e^{-\frac{(y_i-\mu_{y_i})^2}{2\sigma^2}}dy_i$$

□

Theorem 2. *For a protocol $\mathcal{P}$ which uses PRR × d as the metric for choosing forwarding links, the probability of choosing link l_i over all other links, can be expressed as below:*

$$L(\mathcal{W},\mathcal{P},i)$$

$$= P\left(PRR(y_i)*d_i = Max\{PRR(y_j)*d_j : 1\le j\le n\}\right)$$

$$=\sum_{k=0}^{n}\int_{a_k}^{a_{k+1}}\frac{1}{\sigma\sqrt{2\pi}}\left[\prod_{j=1}^{k}\left(\frac{1}{2}+\frac{1}{2}erf\left(\frac{g(\beta_j)-\mu_{y_j}}{\sqrt{2}\sigma}\right)\right)\right]$$

$$\left[\prod_{j=k+1}^{n}\left(\frac{1}{2}+\frac{1}{\sqrt{\pi}}\left(z_j-\frac{z_j^3}{3}+...\right)\right)\right]e^{-\frac{(y_i-\mu_{y_i})^2}{2\sigma^2}}dy_i$$

, where $z_j=\frac{y_i-\mu_{y_j}}{\sigma\sqrt{2}}$, y_i, y_j are SNR (dB) values of link l_i, l_j, $i\ne j$, $a_0=-\infty, a_{n+1}=\infty$, $a_1\le a_2\le ...\le a_n$, $g(\beta_j)=a_j$ if $\beta_j(=\frac{d_j}{d_i})\ge 1$, $g(\beta_j)=\infty$ if $\beta_j<1$

Proof.

$$L(\mathcal{W},\mathcal{P},i)$$

$$= P\left(PRR(y_i)*d_i = Max\{PRR(y_j)*d_j : 1\le j\le n\}\right)$$

$= P(PRR(y_i)*d_i > PRR(y_1)*d_1 \wedge ... \wedge PRR(y_i)*d_i > PRR(y_n)*d_n)$

, where $i\ne j, j=1,..,n$, n is the number of links

Let's put

$$f(.)=\frac{1}{(\sigma\sqrt{2\pi})^n}e^{-\frac{(y_1-\mu_{y_1})^2+...+(y_n-\mu_{y_n})^2}{2\sigma^2}}$$

Because the conjunctions of the conditions will be translated into multiple integrals. Apply Theorem 1 here,

$$=\int_{-\infty}^{a_1}\int_{-\infty}^{y_i}...\int_{-\infty}^{y_i}f(.)dy_n...dy_1dy_i$$

$$+\int_{a_1}^{a_2}\int_{-\infty}^{g(\beta_1)}\int_{-\infty}^{y_i}...\int_{-\infty}^{y_i}f(.)dy_n...dy_1dy_i$$

$$+\int_{a_2}^{a_3}\int_{-\infty}^{g(\beta_1)}\int_{-\infty}^{g(\beta_2)}\int_{-\infty}^{y_i}...\int_{-\infty}^{y_i}f(.)dy_n...dy_1dy_i$$

$$+...$$

$$+\int_{a_n}^{\infty}\int_{-\infty}^{g(\beta_1)}...\int_{-\infty}^{g(\beta_n)}f(.)dy_n...dy_1dy_i$$

$$=\int_{-\infty}^{a_1}\frac{1}{\sigma\sqrt{2\pi}}\left(\frac{1}{2}+\frac{1}{\sqrt{\pi}}\left(z_1-\frac{z_1^3}{3}+...\right)\right)$$

$$...\left(\frac{1}{2}+\frac{1}{\sqrt{\pi}}\left(z_n-\frac{z_n^3}{3}+...\right)\right)e^{-\frac{(y_i-\mu_{y_i})^2}{2\sigma^2}}dy_i$$

$$+\int_{a_1}^{a_2}\frac{1}{\sigma\sqrt{2\pi}}\left(\frac{1}{2}+\frac{1}{2}erf\left(\frac{g(\beta_1)-\mu_{y_1}}{\sqrt{2}\sigma}\right)\right)$$

$$\left(\frac{1}{2}+\frac{1}{\sqrt{\pi}}\left(z_2-\frac{z_2^3}{3}+...\right)\right)$$

$$...\left(\frac{1}{2}+\frac{1}{\sqrt{\pi}}\left(z_n-\frac{z_n^3}{3}+...\right)\right)e^{-\frac{(y_i-\mu_{y_i})^2}{2\sigma^2}}dy_i$$

$$+...$$

$$+\int_{a_{n-1}}^{a_n}\frac{1}{\sigma\sqrt{2\pi}}\left(\frac{1}{2}+\frac{1}{2}erf\left(\frac{g(\beta_1)-\mu_{y_1}}{\sqrt{2}\sigma}\right)\right)...$$

$$\left(\frac{1}{2}+\frac{1}{2}erf\left(\frac{g(\beta_{n-1})-\mu_{y_{n-1}}}{\sqrt{2}\sigma}\right)\right)$$

$$\left(\frac{1}{2}+\frac{1}{\sqrt{\pi}}\left(z_n-\frac{z_n^3}{3}+...\right)\right)e^{-\frac{(y_i-\mu_{y_i})^2}{2\sigma^2}}dy_i$$

$$+\int_{a_n}^{\infty}\frac{1}{\sigma\sqrt{2\pi}}\left(\frac{1}{2}+\frac{1}{2}erf\left(\frac{g(\beta_1)-\mu_{y_1}}{\sqrt{2}\sigma}\right)\right)...$$

$$\left(\frac{1}{2}+\frac{1}{2}erf\left(\frac{g(\beta_{n-1})-\mu_{y_{n-1}}}{\sqrt{2}\sigma}\right)\right)e^{-\frac{(y_i-\mu_{y_i})^2}{2\sigma^2}}dy_i$$

,where $z_k=\frac{y_i-\mu_{y_k}}{\sigma\sqrt{2}}$, y_i, y_k are SNR (dB) values of link l_i, l_k, $i\ne k$

In summary,

$$=\sum_{k=0}^{n}\int_{a_k}^{a_{k+1}}\frac{1}{\sigma\sqrt{2\pi}}\left[\prod_{j=1}^{k}\left(\frac{1}{2}+\frac{1}{2}erf\left(\frac{g(\beta_j)-\mu_{y_j}}{\sqrt{2}\sigma}\right)\right)\right]$$

$$\left[\prod_{j=k+1}^{n}\left(\frac{1}{2}+\frac{1}{\sqrt{\pi}}\left(z_j-\frac{z_j^3}{3}+...\right)\right)\right]e^{-\frac{(y_i-\mu_{y_i})^2}{2\sigma^2}}dy_i$$

□

Next, we propose a procedure for scaling down and transplanting a network protocol to a different RF environment. The basic idea is to optimize transmit power scaling to minimize the distance between the link usage spectrums of the two networks.

Definition 1. *Consider a wireless network* $\mathcal{W}$ *with inter-node distances* $\{d_j\}_{j=1}^m$ *and its scaled version* $\tilde{\mathcal{W}}$*, with inter-node distances* $\{\tilde{d}_j = \alpha d_j\}_{j=1}^m$ *in RF environments characterized by log-normal scale model parameters* (n, σ) *and* $(\tilde{n}, \tilde{\sigma})$ *respectively. We define Transplant Error of a protocol* $\mathcal{P}$ *across the two networks as:*

$$\text{XPlantError}(\mathcal{W}, \tilde{\mathcal{W}}, \mathcal{P}) = \sum_{i=1}^{n} \left| L(W, \mathcal{P}, i) - L(\tilde{W}, \mathcal{P}, i) \right|$$

XPlantError is essentially the l_1 distance between the the link usage spectrums for the two networks $\mathcal{W}$ and $\tilde{\mathcal{W}}$ which differ in scale and RF environment. Theorems 1 and 2 show the relation between the link usage spectrum and performance metric. If we can control the XPlantError within a threshold value, we conjecture that the protocol performance will be similar across scale and environment. We assume that transmit power in the network $\tilde{\mathcal{W}}$ is variable through:

$$\tilde{P}_t = \tilde{P}_0 + \beta \tag{4}$$

where β is the power attenuation or amplification in the scaled network. Since the scaled vector in general reduces the node distances for convenient testing, β in general is a negative value indicating power attenuation. As a result the scaled network realizations $\tilde{\mathcal{W}}(\beta)$ depends on β[1]. The optimal power attenuation is then chosen to minimize the XPlantError metric:

$$\beta_{\text{opt}} = \arg\min_{\beta} \text{XPlantError}(\mathcal{W}, \tilde{\mathcal{W}}(\beta), \mathcal{P}) \tag{5}$$

As shown in [1] if the two networks are in the same environment (i.e. $\eta = \tilde{\eta}$ and $\sigma = \tilde{\sigma}$)) then β can be chosen such that the link SNR realizations y_j and $\tilde{y}_j$ are samples from the same multivariate Gaussian probability distribution. As a corollary, the optimal β in that case would result in identical link usage spectrums. For networks in different RF environments the distribution of link SNR realizations cannot be matched for all link lengths simultaneously and alternative techniques as shown above is required to achieve similar network behavior. In the next section, we will validate the proposed measure of similarity through simulation and experimental studies using linear networks of wireless nodes employing 802.15.4 radios.

[1] We could also introduce spatial variations in β across the nodes to influence the width of the resulting spectrum, for a better match.

3 Simulation and Experimental Studies of Protocol Transplantation

In this section, we present an analytical and experimental study of transplanting a protocol across different WSN environments. We used Collection Tree Protocol (CTP) ([8]) in our experiment, which adopts ETX ([7]) as the routing metric and implemented using 802.15.4 transceivers embedded in popular sensor network platforms such as TelosB and MicaZ. The combination of analytical and experimental results show the effectiveness of the link usage spectrum in assessing protocol behavior and illustrates the optimization power control for transplanting protocols across scale and environment by minimizing the distance between link usage spectrums.

3.1 Experimental Setup

We set up a chain topology with total 20 TelosB ([12]) sensor nodes. Each node is separated by 3 ft and elevated about 4 inches from the ground. TelosB mote is equipped with CC2420 ([10]) radio and USB serial for communication. In [10], TelosB mote uses 2.4GHz frequency and provide 8 different transmission power levels: 31(0dB), 27(-1dB), 23(-3dB), 19(-5dB), 15 (-7dB), 11(-10dB), 7(-15dB), 3(-25dB). We also can attach various attenuators according to achive attenuation levels (1dB, 3dB, and etc.). We used a 3dB attenuator to construct a reasonable communication environment among 20 sensor nodes in a compact indoor area. With transmission power levels of 11 (-10dB), which is -13 dB after 3dB attenuation, we expect 3 $\sim$ 4 hops from the source to the destination, because RF ranging test revealed a maximum communication range with 3dB attenuator in the level 11 is 8 $\sim$ 9 hops.

3.2 Physical & Link Layer

CC2420 ([10]) radio is compatible with the 2.4GHz 802.15.4 standard. 802.15.4 standard wireless physical layer employs block direct-sequence spread spectrum code with 2MChip/s chip rate and 250 kbps data rate to achieve processing and coding gain. The transmitter modulates the carrier using offset quadrature phase shift keying (O-QPSK) with half-sine shaping which is equivalent to minimum shift keying (MSK) modulation which has the following Bit Error Rate:

$$\text{BER} = Q(\sqrt{2y/\text{PG}/\text{CG}}) = \frac{1}{2}\text{erfc}(\sqrt{y/\text{PG}/\text{CG}}) \tag{6}$$

, where y gives the SNR. The processing gain (PG) for 802.15.4 is given by $10\log(2/0.25)$=9 dB. The coding gain (CG) depends on the increased Hamming distance between the codes and is a function of the SNR itself. For low a packet error rate region coding gain can be approximated as 2 dB [14].

Thus, the Packet Reception Rate equation could be calculated form

$$PRR = \left(1 - \frac{1}{2}\text{erfc}(\sqrt{x})\right)^{8*packet\_size}$$

We note that the bit-error-rate approximation given in Equation 6 assumes coherent demodulation using carrier phase information. Practical transceiver designs use non-zero IF and noncoherent demodulation. The non-ideal receiver structures can be approximated with SNR reduction or equivalently increase in the noise floor (P_0) causing only a horizontal shift in the PRR curve.

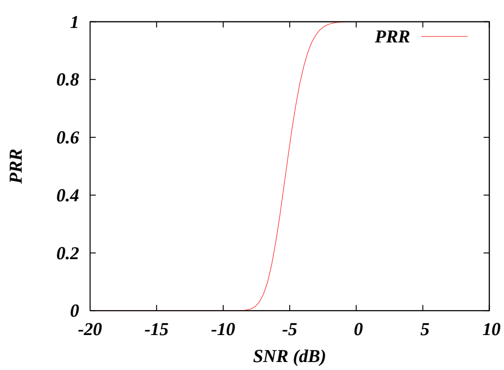

Figure 1: CC2420 Radio: SNR (dB) vs. PRR

Figure 1 shows PRR graph according to the above PRR equation.

To perform analytical study to compare with the experimental results, we require RF environment and radio parameters: Path Loss Exponents (PLE) of indoor and outdoor and standard deviation of RSSI(dB). We performed RSSI measurements in a corridor in the second floor of Dreese Lab Building and on the top of a parking garage building. For indoor test, we measured RSSI at 20 different distances (1 $\sim$ 20 unit (1 unit= 3ft)) within maximum communication range with the highest transmission power level (0dB). For outdoor test, 10 measurements were taken from the distance of 1 $\sim$ 10 unit distances where 30 ft seems to be the maximum communication range with the same transmission power, 0 dB. Figure 2, 3 shows the observed received signal values and the associated log-normal fit. Table 1 presents the summary. We also used reported radio sensitivity of -94 dBm to adjust for the noise power P_0.

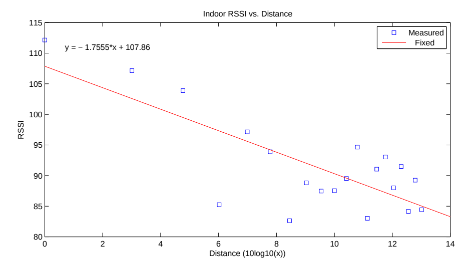

Figure 2: Indoor RSSI vs. Distance

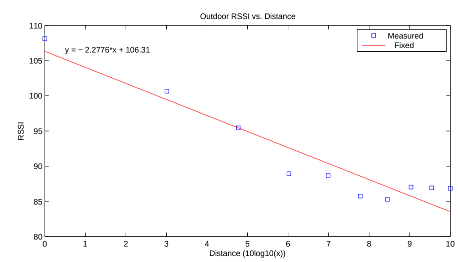

Figure 3: Outdoor RSSI vs. Distance

Metrics	Indoor	Outdoor
Path Loss Exponent	1.7555	2.2776
RSSI Standard Dev.	4.5 dB	4.5 dB

Table 1: Log normal model variables for Indoor and Outdoor RF environments

3.3 Messaging Layer and Experimental Results

We test a messaging layer protocol, CTP ([8]). We first describe briefly how CTP is tested, then we discuss the experimental results.

3.3.1 Collection Tree Protocol

CTP ([8]) is a tree-based collection protocol. Nodes generate routes to roots using a routing gradient.

CTP uses ETX ([7]) as th default routing metric. ETX implicitly favor long links over short links because each node selects the path with the minimum number of expected transmissions. Therefore, we expect ETX works similarly to other metrics which give advantages on long links like PRR× d([6]).

Experimental design In the chain of 20 nodes, the node 0 is set as the sender, and the node at 19 is set as the destination. Every two seconds, the sender produces and sends a packet. For each case, we gathers about 1,000 packets are generated by the source. We logged all the paths that each packet gone through, and only counts the body parts (i.e. excludes the head (the first hop) and the tail (the last hop) of the paths), because usually the head and the tail are composed of the short links as the remainder of the body of a path. The metric used for these experiments are as follows: Average (Median) Link Length and Link Usage Spectrum.

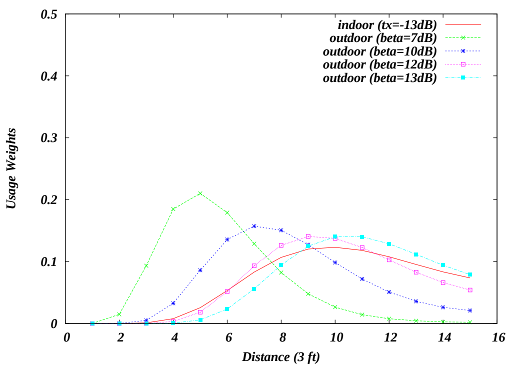

Figure 4: Link Usage Spectrum (Analytical)

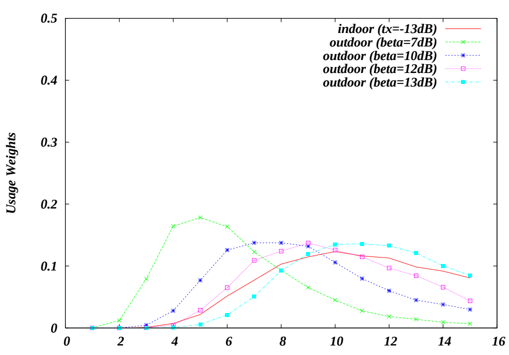

Figure 5: Link Usage Spectrum (Simulation)

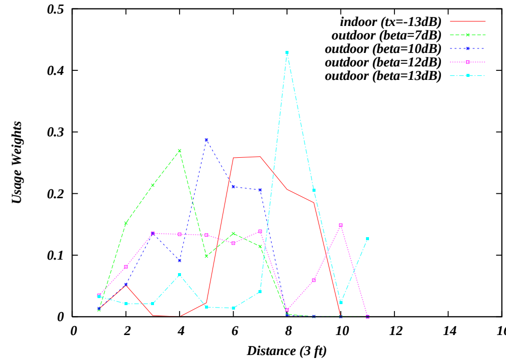

Figure 6: CTP: Link Usage Spectrum (Experimental)

Experimental results Figure 4 and 5 shows the analytical and simulated link usage spectrums for indoor and outdoor environments with β increase in transmission power for outdoor case. The simulation and analytical results are nearly identical supporting the various approximations that were used to achieve to the analytical expressions for link usage spectrum. Figure 6 shows the experiment results of the link usage spectrum. We can see the strong similarities in link usage spectrum between theoretical and experimental results. However CTP with ETX routing metric works more conservatively in choosing the next hop link partly due to the limited size of the network.

XPlantError	β=7	β=10	β=11.5	β=13
Aanlytical	0.9697	0.3386	0.0737	0.282
Simulation	0.937	0.336	0.0658	0.2664

Table 2: Comparison of XPlantError(indoor, outdoor, m)

The performance metrics, average link length and end-to-end delay, will be directly affected by the usage weights. Therefore, if we maintain the usage weights of links in outdoor most similar to indoor case, then we will have the similar performance metrics in ourdoor case. According to Table 2, β should be around 11 $\sim$ 12 dB for both experimental and analytical study.

Link Length	In tx:-13dB	Out β:7dB	Out β:10dB	Out β:12dB	Out β:13dB
Average	6.9329	4.1842	5.0584	5.6603	7.7749
Median	7	4	5	5	8

Table 3: Comparisons of Performance Metrics: Link Length Indoor and Outdoor

e-to-e delay	In tx:-13dB	Out β:7dB	Out β:10dB	Out β:12dB	Out β:13dB
Average	3.712	5.2481	4.4512	3.6489	3.2049
Median	4	5	4	4	3

Table 4: Comparisons of Performance Metrics: End-to-End Delay (or # of transmissions) between Indoor and Outdoor

Table 3 and Table 4 show the average and median values for the performance metrics with each specified transmission powers. By Table 2, 3, and 4 , we can conclude that for the best matching performance between indoor and outdoor, β should be 11∼12 dB, and the analytical study exactly calculate β to minimize XPlantError and to achieve the most similar performance of CTP across two different environments.

4 Discussion

Variations of XPlantError. A generic (i.e., less protocol specific) formulation would simply be to minimize the PRR difference between the respective links in the two networks. In this case, XPlantError would be:

$$\sum_{j=1}^{m} |PRR(y_j) - PRR(\tilde{y}_j)| \tag{7}$$

where $PRR(y_j)$ is the PRR of link l_j in a wireless network W with m links, while a universally applicable metric, this formulation does not consider the choice of the links in matching performance.

Alternatively, one could weigh the link usage spectrum of expected performance metric at SNR, PRR, ETX, EDL, $PRR \times D$

$$\left| \sum_{i=1}^{n} g(y_i|l_i \uparrow) L(W, \mathcal{P}, i) - \sum_{i=1}^{n} g_(\tilde{y}_i|l_i \uparrow) L(\tilde{W}(\beta), \mathcal{P}, i) \right| \tag{8}$$

where $l_i \uparrow$ means l_i is the conditional expectation given the link l_i was chosen. This error metric is bounded above by to distance between the link usage spectrums proposed in this paper.

5 Conclusions and Future Work

In this paper, we provided a technique for reproducing protocol behavior comparable to that of one network in another network. Our technique accommodates network pairs whose signal propagation characteristics and inter-node spacings may be different. It consists of three parts: First, the link usage spectrum is calculated analytically (or alternatively by simulation or experiment); our illustration was in terms of one specific protocol metric for choosing the forwarding links, but the approach itself is applicable more generally. Second, the XPlantError is defined in terms of their respective link usage spectrums to quantify the behavioral difference of the protocol in question in the two networks. Third, an optimal mapping point and corresponding transmission power adjustment is chosen for the target network that minimizes the XPlantError. Our analytical and experimental results provide a case study that validate this techniques ability to achieve predictable performance while transplanting protocols, which is in our opinion a basic problem.

In the future, we will study how to redress the limitations of the link usage spectrum discussed in the previous section, focusing in particular on providing a continuous version of the concept which allows network nodes to be placed at random points in a geometric space. We will explore predictable performance in transplanting networks, using knobs other than the transmission power control and taking into account metrics other than those related to the forwarding link selection alone. We will also study the variability of protocol behavior in one network, possibly using a sigma point filtering method, and account for the preservation of that variability in transplantation, over and above the median/average behavior that we have focused on in this work.

References

[1] V. Naik, E. Ertin, H. Zhang, A. Arora. Wireless Testbed Bonsai, *2nd International Workshop on Wireless Network Measurement*, 2006

[2] V. Naik, A. Arora, P. Sinha, H. Zhang. Sprinkler: A Reliable and Energy Efficient Data Dissemination Service for Wireless Embedded Devices, *26th IEEE Real-Time Systems Symposium*, 2005

[3] H. Zhang, A. Arora, P. Sinha. Learn on the Fly: Data-driven Link Estimation and Routing in Sensor Network Backbones, *25th IEEE International Conference on Computer Communications*, 2006

[4] http://exscal.nullcode.org/kansei

[5] M. Zuniga and B. Krishnamachari. Analyzing the transitional region in low power wireless links, *IEEE SECON*, 2004

[6] K. Seada, M. Zuniga, A. Helmy, B. Krishnamachri. Energy-Efficient Forwarding Strategies for Geographic Routing in Lossy Wireless Sensor Networks, *Sensys*, 2004

[7] D. Couto, D. Aguayo, J. Bicket, R. Morris. A High-Throughput Path Metric for Multi-Hop Wireless Routing, *Mobicom*, 2003

[8] TEP 123, http://www.tinyos.net/tinyos-2.x/doc/html/tep123.html

[9] T. S. Rappaport. Wireless Communications: Principles and Practice, Prentice Hall

[10] Chipcon. Chipcon cc2420 datasheet, http://www.chipcon.com/files/CC2420_Data_Sheet_1_4.pdf

[11] IEEE 802.15.4, http://standards.ieee.org/getieee802/download/802.15.4-2006.pdf

[12] C. Technology Telosb datasheet. http://www.xbow.com/Products/Product_pdf_files/Wireless_pdf/TelosB_Datasheet.pdf

[13] J. Zhao, R. Govindan, Understanding Packet Delivery Performance in Dense Wireless Sensor Networks, *Sensys*, 2003

[14] S. Lanzisera, K. Pister, Theoretical and Practical Limits to Sensitivity in IEEE 802.15.4 Receivers, *IEEE International Conference on Electronics, Circuits and Systems*, 2007