

On the Packet Loss Correlation in Wireless Mesh Networks: Channel Models and Practical Schemes

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ABSTRACT

State-of-the-art analysis and protocols in wireless mesh networks typically assume an independent packet loss channel for each receiver of a transmission. Although this is usually transparent for single-path protocol design, this assumption may severely degrade the performance of opportunistic and/or multi-path routing approaches as well as network coding (NC) subgraph selection problems (routing in NC). This paper proposes simple channel models to incorporate the effect of correlation between receivers in a parametric fashion and supports them with a measurement campaign that leverages various commercial devices and network conditions. Finally, we illustrate the effect of correlation in the design and performance of the PlayNCool network coding protocol introduced by the authors in prior work. Our results show that the modified PlayNCool protocol decreases the overhead by a factor of 2.5x.

Categories and Subject Descriptors

C.2.1 [COMPUTER-COMMUNICATION NETWORKS]: Wireless communication; E.4 [CODING AND INFORMATION THEORY]: Formal models of communication

Keywords

Network Coding; Wireless Mesh Networks; Protocol Design

1. INTRODUCTION

Recently, the use of opportunistic protocols and multipath protocols that rely on the broadcast nature of the wireless channel to transmit information have improved the performance of wireless mesh networks. This trend has been bolstered by the introduction of network coding, a technique that allows to transmit linear combinations of the data packets and which inherently simplifies protocols and increases the potential of overhearing in wireless mesh networks.

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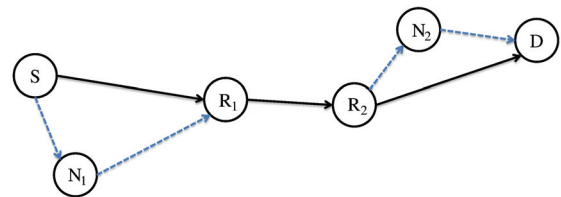


Figure 1: Routing protocol find different paths from the source to the the destination. The bold lines correspond to standard protocols, while the dashed ones are potential options due to opportunistic approaches.

ExOR is the first implementation of an opportunistic routing protocol [2], with the caveat that nodes should coordinate their action to avoid transmissions of redundant packets. To address this problem, MORE [3], CCACK [6], GeoCode [11], CORE [7], exploit random linear network coding (RLNC) to reduce the coordination between nodes.

Modeling the characteristics of packet reception across multiple receivers is paramount to understanding and characterizing the impact of these novel protocols. Most of the protocols are assumed that the propagation channels between each pair of transmit and receive antennas is statistically independent and identically distributed. In practice, the channels between different antennas are often correlated [8].

To the best of our knowledge, simple and useful channel models that capture correlation are missing in the literature. In this paper, we introduce a new channel model that captures the effect of correlation across various receivers. The proposed model parameterizes the channel properties to calculate the correlation of the channel. The parameters of this model can be used to design and develop new network protocols. To understand the effect of the correlation, we study the effect of the correlation in different platforms (laptops, Raspberry Pi) and we validate our model by following a measurement campaign in commercial devices. Then, we modify a network coding protocol called PlayNCool [11] based on the new model parameters. The modified version of the PlayNCool protocol considers the correlation between channels. Our measurement results in a Raspberry Pi test-bed show that considering the correlation in our de-

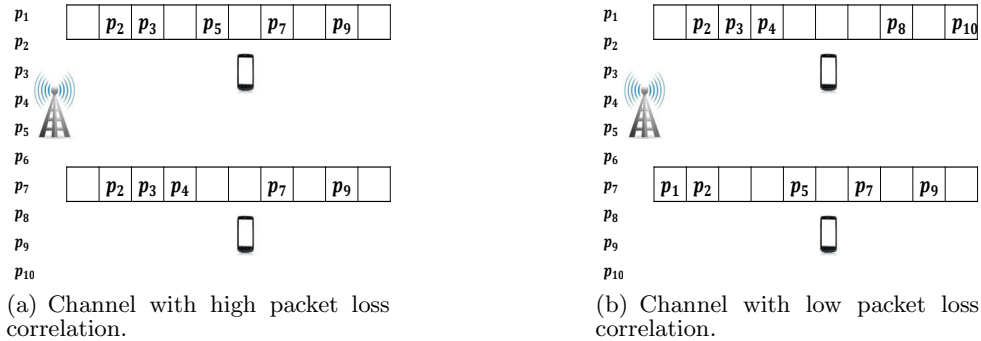


Figure 2: Example of a channel with high (a) and low (b) packet loss correlation. For (a) both receivers predictably get a similar subset of the data packets. For (b) the receivers may collect different subsets of the transmitted data packets.

sign, the transmission of the linear dependent packets will be decreased by a factor of 2.5x, thus increasing the efficiency of the overall scheme.

The remainder of the paper is organized as follows. In Section 2, we describe the motivation and the need to consider the correlation in the channel. Then, we illustrate our channel model in Section 3. Section 4 provides the modification of the PlayNCool protocol considering the new channel model. The measurement of the modified PlayNCool and its performance comparison are presented in section 4. Finally, Section 6 concludes the paper.

2. MOTIVATION

Traditional routing protocols use a single path to transmit packets from the source node to the destination node in wireless mesh networks such as DSR [4], AODV [12], and BATMAN [9]. In Fig. 1, solid lines show the single path from the source to the destination. The path is selected based on different criteria such as number of hops, delay, and jitter. This approach is similar to the wired networks and it does not exploit the broadcast property of the wireless networks. However, in the wireless networks, the nodes can overhear the transmitted packets from other nodes. The overhearing of a packet offers interesting potential to each nodes to forward received packets opportunistically.

Recently, the opportunistic routing protocol (OR) has exploited the broadcast property of the wireless network to boost the performance of the communication in wireless networks. In this approach, each neighbor can overhear the packets and forward the overheard packets to the next hop opportunistically. In Fig. 1, the dashed lines are potential options due to opportunistic approaches. Neighbors of the main path build the extra path by overhearing the packets and transmitting them to the next hop.

The advantage of the opportunistic overhearing and forwarding is dependent on the channel correlation factor. Let us use an example to illustrate the effect of correlation of the channels to the throughput of the wireless networks. In Fig. 2, the source broadcasts 10 packets to two destinations. Each destination receives five of them. Fig. 2(a) shows the case of correlated channel where most of the received packets are the same for both destinations. However, Fig. 2(b) shows the case of low correlated channel where most of the received packets in both destinations are different. Consid-

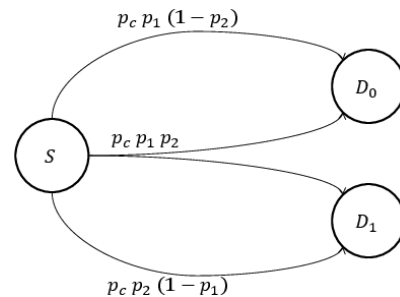


Figure 3: The channel model. There are three imaginary channel between the source and the destinations.

ering that one of the destination in the Fig. 2 is the relay of the main path of the data flow in Fig. 1, In the case of the high correlation, the neighbor of that node must transmit less number of packets to the destination. However, in the case of low correlation, the neighbor has more transmission options. Thus, opportunistic overhearing benefits more from low correlated channels. When the network is dense and the channels are highly correlated, the source knows that by receiving one packet to one of the destination, the others also received the same packets with high probability. So it reduces the need of the feedback mechanism in the nodes. In any cases, the network coding reduces the coordination overhead between the neighbors and the relay.

Several aspects have effect on the correlation between two channels. Based on the position of the nodes, The correlation value is different for different sources and different receivers. To understand the correlation value for different channel pairs we present a measurement campaign on commercial devices. A testbed consisting of five Lenovo Thinkpad X210T laptops using the Ubuntu 12.04 64-bit operating system. The testbed is deployed in an office-space environment according to the floor plan in Fig. 4.

The correlation value for this testbed is shown in Fig. 5 for different source nodes. The source broadcasts the packets to the all destinations. As it shown in in this figure, the correlation value is different for different channels and nodes. In this deployment the correlation for different sources has a range from 0 to 0.5.



Figure 4: Floor plan for measurement campaign in Berlin consisting of five Lenovo Thinkpad X210T laptops.

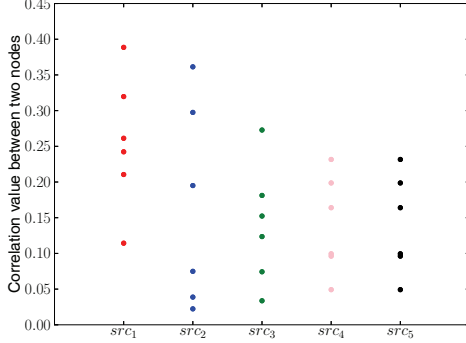


Figure 5: The correlation between different nodes for laptop testbed when the different sources are transmitting in the channel.

3. CHANNEL MODEL

In this section, we introduce a model to parameterize correlated channels. Fig. 3 shows the basic topology of the model. The source S is broadcasting packets to D_1 and D_2 . We define X and Y as a random variable of successful transmission from S to D_1 and D_2 , respectively. They have Bernoulli distribution property because $P(X = 1) = 1 - P(X = 0)$. This topology has three imaginary channels for transmission. The first channel is dedicated to transmit to D_1 and not to D_2 , the second channel is dedicated to transmit to D_2 but not to D_1 , and the third channel is dedicated to transmit to both D_1 and D_2 at the same time. We define p_c , p_1 , and p_2 are the three parameters to model success probability of transmission to each channel. Fig. 3 shows the probability of successful transmission for introduced imaginary channels which is $p_c \cdot p_1 \cdot (1 - p_2)$, $p_c \cdot p_2 \cdot (1 - p_1)$, and $p_c \cdot p_2 \cdot p_1$, respectively. Thus, the probability of successful transmission to D_1 is $p_c \cdot p_1$ and the probability of successful transmission to D_2 is $p_c \cdot p_2$.

In a sense, p_c indicates the dependency of the reception to D_1 and D_2 . The closer p_c is to 0, the stronger dependency between reception of two nodes. As p_c approaches to one there is less of a dependency between two nodes.

The correlation $\rho(x, y)$ for two random variables X and Y with expected values μ_X and μ_Y and standard deviations σ_X and σ_Y is defined as [1]:

$$\rho(x, y) = \text{corr}(X, Y) = \frac{\text{cov}(X, Y)}{\sigma_X \sigma_Y}, \quad (1)$$

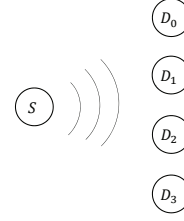


Figure 6: The topology of the test-bed. The source broadcasts the packets to the four destinations.

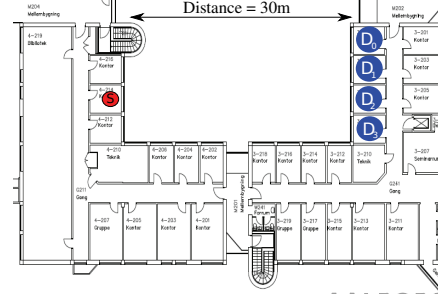


Figure 7: The Raspberry Pi testbed deployment in a Aalborg University building. The red spot indicates the source location and the blue spot indicates the the destination location.

where $\text{cov}(X, Y)$ is the covariance of two random variables. By using $\text{cov}(X, Y) = E[X, Y] - \mu_X \cdot \mu_Y$:

$$\rho(x, y) = \text{corr}(X, Y) = \frac{E[X, Y] - \mu_X \cdot \mu_Y}{\sigma_X \sigma_Y}. \quad (2)$$

The standard deviation of Bernoulli random variable for X is equal to $\sqrt{p_c \cdot p_1 \cdot (1 - p_c \cdot p_1)}$ and for Y is equal to $\sqrt{p_c \cdot p_2 \cdot (1 - p_c \cdot p_2)}$, the mean value is equal to $p_c \cdot p_1$ for X and $p_c \cdot p_2$ for Y , and E is the expectation which is equal to:

$$E[X, Y] = \sum_{i=0}^1 \sum_{j=0}^1 p(x, y) = p_c \cdot p_1 \cdot p_2. \quad (3)$$

By using the Eq. 3 and Eq. 2 the correlation is equal to:

$$\text{corr}(X, Y) = \frac{p_1 \cdot p_2 \cdot (1 - p_c)}{\sqrt{p_1 \cdot p_2 \cdot (1 - p_c \cdot p_1) \cdot (1 - p_c \cdot p_2)}}. \quad (4)$$

Correlation value comparison

In order to validate our channel model, we compare the correlation value obtained by our channel model with the measured correlation using the Pearson model. The value of p_1 , p_2 , and p_c are a function of different parameters in the network such as the antenna and transmission environment. We used Raspberry Pi devices using ubuntu operating system and TL-WN722N Wifi devices to transmit data in wireless channel. The topology of the test-bed includes one source and four destinations as shown in Fig. 6. The source broadcast UDP flow to the destination. All nodes are using

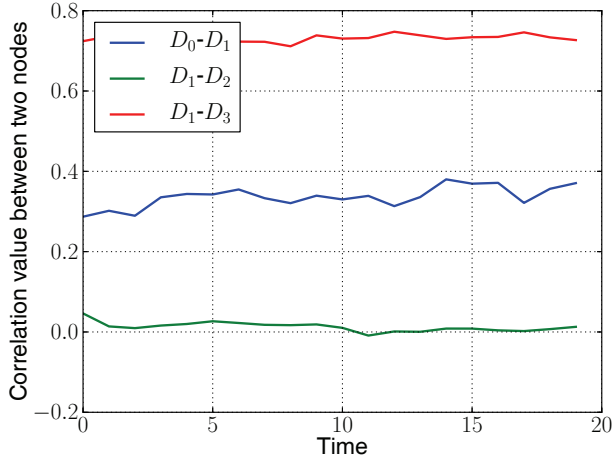


Figure 8: Correlation variation over time for different pairs of the nodes.

2412 MHz to transmit and receive data packets. The measurement is taken in the Department of Electronic System of the Aalborg University with the placement as given in Fig. 7. The red point is the source node and the blue points are all the destinations. The source broadcasts the packets to all of the destinations. Each destination records the information about the received packets and then it delivers all recorded information to a master computer. The recorded information later is used to calculate the correlation value.

As it shown in Fig. 9, the measured correlation value using Pearson model is as same as the new model. Thus, the proposed model can predict the channel dependency very well. Fig. 8 shows the evolution of the channel correlation over time for three pair of channels. The measurement divided into 20 blocks over a period of time. As it shown in this figure the correlation value is quite stable and it is not fluctuating a lot over time.

4. EFFECT OF CHANNEL CORRELATION IN THE PLAYNCOOL PROTOCOL

In order to evaluate the impact of correlated channels errors, we apply our findings at the PlayNCool protocol. In [10, 5], we proposed the PlayNCool protocol to improve the performance of communication by selecting a local helper between nodes to fortify the quality of each link. The PlayNCool protocol increases the end-to-end gain by factor of two to four folds in the wireless mesh network. However, PlayNCool does not consider the correlation between channels. Each node may transmit linear dependent packets when the correlation between channels is high. The value of error correlation between the helper and the destination has a significant impact on the gain. Specially, when the helper is close to the destination, the probability of receiving a packet in the helper and the destination is highly correlated. In fact, by increasing the distance between the helper and the destination, the error correlation between the helper and the destination decreases. Having the high value of the error correlation makes the helper inefficient because the helper receives the same DOFs as the destination with high prob-

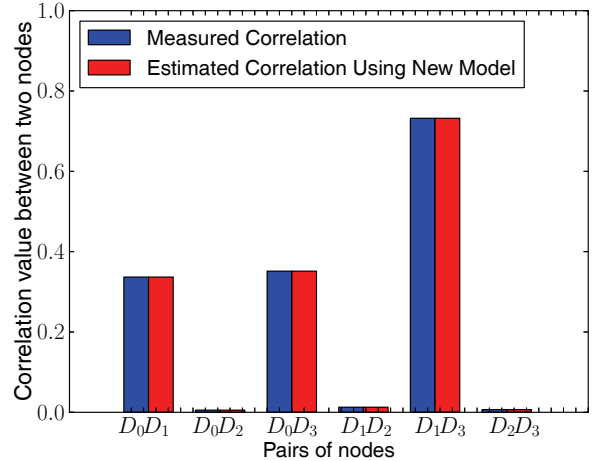


Figure 9: Comparison of the measured correlation value with proposed model for the Raspberry Pi deployment in Fig. 7.

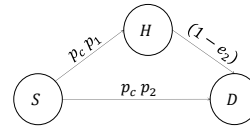


Figure 10: PlayNCool topology.

ability. Degrees of freedom corresponds to the number of independent linear combinations received or available to a node in the network.

4.1 System Model

The basic topology of the PlayNCool is shown in Fig. 10 including a source, a helper, and a destination. The source (S) transmits coded packets to the destination (D). The helper H overhears the coded packets from S and stores them for generating new coded packets. The packet loss probabilities of the different links are illustrated in Fig. 10, where the successful transmission between S and H , H and D , and S and D are represented by $p_c \cdot p_1$, $1 - e_2$, and $p_c \cdot p_2$, respectively. The source generates coded packets by linear combination of generation of g packets using coefficients drawn uniformly at random from the elements of the finite field of size q , i.e., $GF(q)$. We assumed that q is large enough so that any RLNC packet received from the source is independent from previously received packets with very high probability.

The helper H accumulates the coded packets by overhearing transmissions from the source. When it has accumulated enough coded packets, it generates coded packets by recoding, i.e., by creating linear combinations of the buffered coded packets, and transmits them to the destination. At this point, both the source and the helper continue to transmit coded packets to the destination until the destination acknowledge that it has all g DOF. Then, the source stops transmitting the current generation and starts transmitting the new generation.

The destination includes a bit map of the received packet into the header of the acknowledgment packet. The bit map

shows the received packets and lost packets in the destination. The size of the bit map is equal to the number of transmitted packets from the source. For example, when the source has transmitted 200 packets to deliver a generation of 100 packets, the size of the bit map would be 100 bits which is negligible. The helper uses the bit map information to compute the channel correlation between the source to the helper and the source to the destination. As we showed in Fig.8, the correlation of the channel is stable for long period of time. Thus, the helper can use the bitmap information for long period of the time without updating.

4.2 Helper waiting time

In this section we calculate the number of accumulated packets in the helper before it starts helping. The helper should receive enough innovative packets before start sending. The number of received DOF must be large enough that the receiver does not receive any non-innovative packets from the helper. Given that the desired outcome is for the number of received coded packets to be equal to g , then $g = r \cdot p_c \cdot p_2 + k \cdot (1 - e_2) + k \cdot p_c \cdot p_2$, and thus,

$$k = (g - r \cdot p_c \cdot p_2) / (1 + p_c \cdot p_2 - e_2). \quad (5)$$

The number of received DOF in the helper should be at least equal to the number of transmitted DOF from helper. Therefore, the subtraction of received DOF and transmitted DOF is considered to be zero:

$$r \cdot p_c \cdot p_1 \cdot (1 - p_2) + k \cdot p_c \cdot p_1 \cdot (1 - p_2) - k \cdot (1 - e_2) = 0. \quad (6)$$

By combining Eq. 5 and Eq. 6 we can calculate as a following:

$$k = \frac{g \cdot p_1 \cdot (1 - p_2)}{(1 - e_2) \cdot (p_2 + p_1 \cdot (1 - p_2))} \quad (7)$$

$$r = \frac{g \cdot ((1 - e_2) - p_c \cdot p_1 \cdot (1 - p_2))}{p_c \cdot (1 - e_2) \cdot (p_2 + p_1 \cdot (1 - p_2))} \quad (8)$$

5. PERFORMANCE EVALUATION

In this section, we compare the performance of modified version of the PlayNCool with the original PlayNCool protocol. The recorded information of Raspberry Pi devices is used to illustrate the performance modified version of PlayNCool in the presence of correlated losses. We demonstrate that by considering the channel dependency in the design of the PlayNCool protocol, the number of transmission of the linear dependent packets will be decreased.

The modified PlayNCool protocol

We used packet reception trace of Fig. 7 test-bed to illustrate the performance of the modified PlayNCool protocol. Node D_0 is chosen as the helper and node D_1 as the destination from Fig. 6. The error probability for the channel between the helper and the destination is 0.1. As it shown in Fig.11(a), the average number of linear dependent packets received in the destination is less when the modified version of PlayNCool is used. The reason is that the modified-PlayNCool takes the dependency of the channels into account, therefore the helper transmits less number of linear dependent packets to the destination.

Fig. 12 shows the total number of transmissions for both original and modified version of the PlayNCool approach for different e_2 . As shown in this figure, the number of the

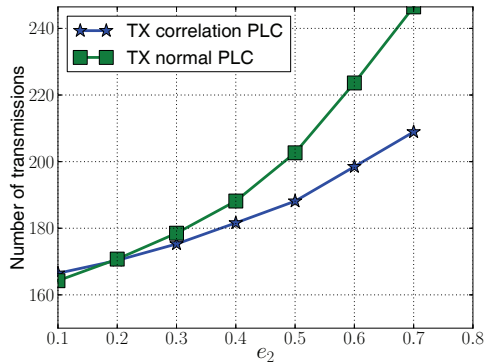


Figure 12: Total number of transmitted packet for standard PlayNCool and correlation based PlayNCool.

modified version of the PlayNCool is less than the original PlayNCool for higher e_2 . The reason is that the lower success probability between the helper and the destination, the higher number of transmissions from the helper to the destination. Thus, the effect of the correlation in the total number of transmission for higher error probability is more tangible.

6. CONCLUSION

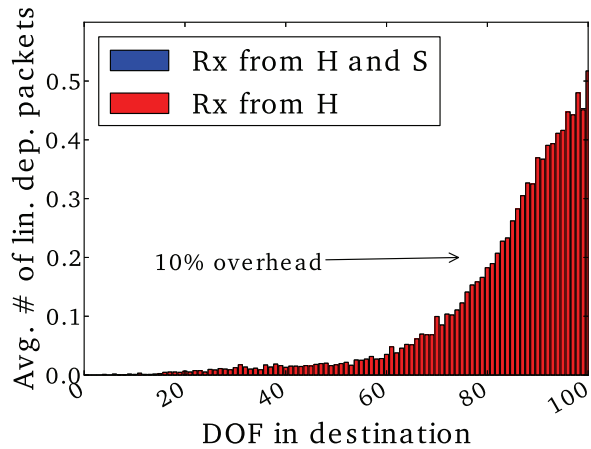
In this paper, we studied the effect of the correlation in different platforms (Laptops and Raspberry pi) and we introduced a new channel model to incorporate the effect of correlation of losses between receivers in a parametric fashion. We supported our model with a measurement campaign that leverages commercial devices and various network conditions. We also presented the effect of correlation in the design of the PlayNCool protocol. The implementation and measurements using Aalborg University's Raspberry Pi test bed proved that the modified PlayNCool protocol decreases the transmission of the linear dependent packets. Our future work will focus on the using more nodes and also the effect of geographical position of the nodes on the correlation.

Acknowledgment

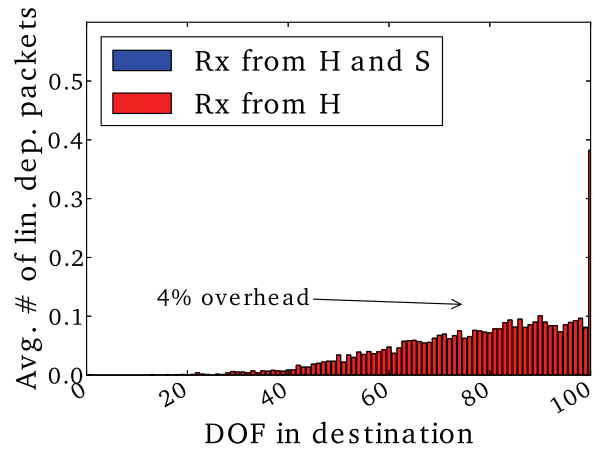
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(a)



(b)

Figure 11: The average number of linearly dependent packets received in the destination from the source and the helper for certain DOF in the destination when $g = 100$, $e_2 = 0.1$. (a) The standard PlayNCool approach (b) modified PlayNCool for correlated channels.

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