Impact of Network Resource Constraints on the Performance of Wireless Sensor Relay Networks

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ABSTRACT

This work studies the impact of the network resource constraints on the performance of wireless sensor multi-hop relay networks. A differential space-time coding and the cooperative relay scheme for cross layer design is introduced in multi-hop wireless sensor networks. To analyze the network performance of such a system, the relay system from source to destination is simplified as a virtual bit pipe line, and a Markov chain model as well as an M/G/1 queueing system are used. The closed form expression for throughput and delay are derived in the infinite buffer case. A truncated Markov chain model and an M/G/1/K queueing system are used to model the finite buffer situation. Moreover, the system drop probability and the go through delay are studied based on the models.

Categories and Subject Descriptors

C.2 [**Computer Systems Organization**]: Computer- Communication Networks

General Terms

Performance

Keywords

Multi-hop sensor network, Markov chain, skip-free negative, M/G/1.

1. INTRODUCTION

Wireless sensor networks can provide solutions environment monitoring for many civil and military applications [1]. The parallel relays [6][7], using space-time modulation and cross-layer design, are the contender against the traditional routing protocol[4]. Assuming a source is broadcasting and can be heard by multiple neighbor nodes simultaneously, a pair of nodes with high link quality can be selected as relay nodes to bring cooperative diversity into the routing process. In doing so, each pair of relay nodes receive signal from the previous hop and retransmit the data *in parallel* to the next hop via Space-time coding and scheduling. After multi-hops of relay, the destination detects the symbol sequence transmitted from the source with the space diversity provided by the relay nodes.

In this work, we analyze the performance of such a system previously proposed in [5] from the network aspect. In considering the packet passing through the network via the virtual bit pipe from the source to the sink, we first model the relay system using a Markov chain. The system performance is then studied using the stationary distribution of the Markov chain. We also use the M/G/1 queueing system [2] to analyze the system performance. The network resource such as, energy, power, computation ability and memory of each tiny sensor node is limited, a system with finite buffer size is more practical than one with infinite buffer size. We also use these two models to analyze the impact of the system buffer size on the network performance (the probability of drop and go through delay).

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IWCMC'06, July 3–6, 2006, Vancouver, British Columbia, Canada.
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2. A BRIEF ON THE DSTBC COOPERATIVE RELAY

In this work, we consider a wireless sensor network, where the block fading channel coefficients between the source node and the relay nodes are statistically independent, but remain unchanged within T symbol periods. The source node sends a set of data $\mathbf{d}$, to the remote sink node through a multi-hop network, as shown in Figure 1. With the traditional single relay method, in the intermediate hop j, only one node is chosen to retransmit the data to $j+1$ hop. While in the cooperative relay scheme, two nodes perform relay with differential Space-time block code (DSTBC) encoding to the next hop. The transmitted signal matrices can be written as

$$\begin{cases} \mathbf{S}_0^{(j)} = \mathbf{I} \\ \mathbf{S}_t^{(j)} = \mathbf{D}_t^{(j)} \mathbf{S}_{t-1}^{(j)} \end{cases} \tag{1}$$

where

$$\mathbf{D}_t^{(j)}(\mathbf{d}) = \frac{1}{\sqrt{2}} \begin{bmatrix} d_1^{(j)}(t) & d_2^{(j)}(t) \\ -d_2^{*(j)}(t) & d_1^{*(j)}(t) \end{bmatrix}$$

contains data $\mathbf{d}$. The received data at the $j+1$ hop relay nodes ($\text{Node}_{j+1,1}$ and $\text{Node}_{j+1,2}$) over two consecutive time

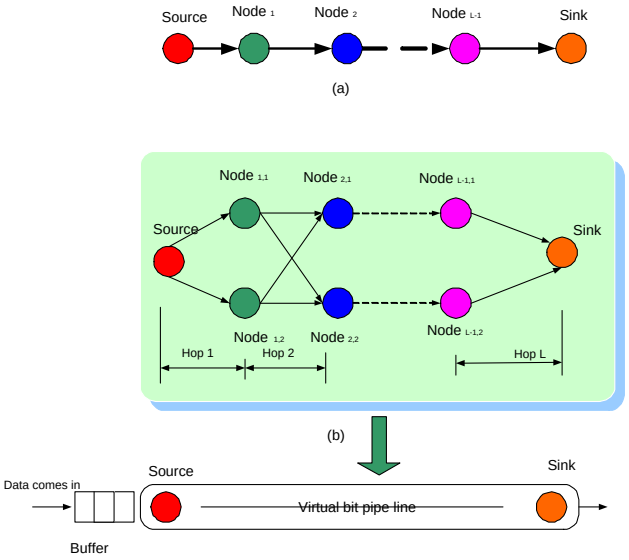

Figure 1: A multi-hop relay wireless network and the simplified virtual bit pipe line (a) single relay (b) cooperative relay.

slots are

$$\mathbf{X}_t^{(j+1)} = \rho \mathbf{H}^{(j,j+1)} \cdot \mathbf{S}_t^{(j)} + \mathbf{W}_t^{(j+1)} \tag{2}$$

with

$$\mathbf{X}_t^{(j+1)} = \begin{bmatrix} x_{1,1}^{(j+1)}(t) & x_{1,2}^{(j+1)}(t) \\ x_{2,1}^{(j+1)}(t) & x_{2,2}^{(j+1)}(t) \end{bmatrix}$$

and

$$\mathbf{H}^{(j,j+1)} = \begin{bmatrix} h_{1,1}^{(j,j+1)} & h_{1,2}^{(j,j+1)} \\ h_{2,1}^{(j,j+1)} & h_{2,2}^{(j,j+1)} \end{bmatrix}$$

where ρ is the square root of the signal to noise ratio, $\mathbf{H}^{(j,j+1)}$ is the channel coefficient matrix between the hop j relay nodes and the hop $j+1$ relay nodes, the noise matrix $\mathbf{W}_t^{(j+1)}$ contains complex i.i.d. gaussian samples.

Since (1) is the standard differential STBC coded signal, the traditional differential decoding algorithm can be applied without the need for estimating the channel coefficient, which performs the maximum likelihood decoding with a linear complexity[9].

$$\begin{aligned} &\begin{bmatrix} \hat{d}_1^{(j)}(t) & \hat{d}_2^{(j)}(t) \end{bmatrix} \\ &= \begin{bmatrix} x_{1,1}^{(j+1)}(t) & x_{1,2}^{*(j+1)}(t) \end{bmatrix} \begin{bmatrix} x_{1,1}^{*(j+1)}(t-1) & x_{1,2}^{*(j+1)}(t-1) \\ x_{1,2}^{(j+1)}(t-1) & -x_{1,1}^{(j+1)}(t-1) \end{bmatrix} \\ &+ \begin{bmatrix} x_{2,1}^{(j+1)}(t) & x_{2,2}^{*(j+1)}(t) \end{bmatrix} \begin{bmatrix} x_{2,1}^{*(j+1)}(t-1) & x_{2,2}^{*(j+1)}(t-1) \\ x_{2,2}^{(j+1)}(t-1) & -x_{2,1}^{(j+1)}(t-1) \end{bmatrix} \end{aligned}$$

This process is repeated at each hop until the transmitted signals finally reach the sink. The combination of the transmission, relay, receiving and decoding from the source to the sink appears to higher layers as a virtual bit pipe with a bit error rate (P_e). In the next section, we will show the role of P_e in the expression of throughput and delay.

3. PERFORMANCE ANALYSIS USING MARKOV CHAIN AND SKIP FREE NEGATIVE PROCESS

We analyze the performance of system from the view point of the network. The throughput and the average end-to-end delay are the most important performance measures of a data network. Furthermore, throughput and delay consideration strongly influence the choice of network algorithm. Queueing theory is the primary methodological framework for analyzing network performance. It often uses simplifying assumption since more realistic assumption makes analysis extremely difficult. Consider a packet arrives for service at the source, the virtual bit pipe line (from the source to the sink) as a server to provide the packet delivering with BER (P_e), the service time for a packet equals the time needed for packet transmission, relaying, receiving and decoding.

3.1 Markov Chain and Steady State Model

Consider a queueing system where packets arrival follows the Poisson distribution with rate λ. Define the system state as the number of packets in the system (packets waiting in the buffer plus packet undergoing service) and the service time for one packet as τ.

The probability that k data packets come into the buffer during time τ is:

$$P\Big(N(t+\tau) - N(t) = k\Big) = \frac{(\alpha)^k}{k!} e^{-\alpha}, \tag{3}$$

where $\alpha = \lambda\tau$. The transition probability $P_k = P_{i,i+k}$ is

$$\begin{aligned} P_{-1} &= e^{-\alpha} P_{ST} \\ P_0 &= e^{-\alpha} P_{FT} + \alpha e^{-\alpha} P_{ST} \\ P_k &= \frac{(\alpha)^k}{k!} e^{-\alpha} P_{FT} + \frac{(\alpha)^{k+1}}{(k+1)!} e^{-\alpha} P_{ST}, \quad k > 0 \end{aligned} \tag{4}$$

where $P_{ST} = (1 - P_e)^{Len}$ is the probability for successful transmission, Len is the length of the packet, P_e is the bit error rate, and $P_{FT} = 1 - P_{ST}$ is the probability of transmission failure.

The system can be modeled as a Markov chain, as shown in Figure 2. The corresponding transition probability matrix is

$$\mathbf{P} = \begin{pmatrix} P_0 + P_{-1} & P_{-1} & 0 & \cdots & 0 \\ P_1 & P_0 & P_{-1} & \cdots & 0 \\ P_2 & P_1 & P_0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \end{pmatrix}$$

and it is a skip free negative process [3]. Denote the stationary probability distribution of the system as $\boldsymbol{\pi} = [\pi_0\ \pi_1 \cdots]^T$.

We have the balance equation:

$$\mathbf{P}\boldsymbol{\pi}^T = \boldsymbol{\pi}^T$$

Define the generating function $P(z) = \sum_{i=0}^{\infty} P_i z^i$ and $\pi(z) = \sum_{k=0}^{\infty} \pi_k z^k$, then solving for $\pi(z)$

$$\pi(z) = \frac{P_{-1}\pi_0(z-1)}{z - P_{-1} - zP(z)}$$

Using the fact that $\pi(1) = 1$, along with L'Hôpital's rule,

we find that

$$\pi_0 = \frac{\mu}{P_{-1}} \tag{5}$$

with $\mu = -\sum_{i=-1}^{\infty} iP_i = P_{ST} - \alpha$. The system with infinite buffer is null recurrent if $\mu = 0$, transient if $\mu < 0$, and has a stationary distribution if and only if $\mu > 0$ which is $P_{ST} > \alpha$, i.e., there are packets waiting, the probability of success must be greater than the average number of new arrivals. So, P_{ST} is the system capacity. Define the throughput as the average number of the successfully transmitted data packets per period,

$$R = \sum_{i=1}^{\infty} \pi_i \cdot P_{ST} + \pi_0 \left(1 - \frac{\alpha^0}{0!} e^{-\alpha}\right) P_{ST}$$

The average number of packets in system is $L_s = \sum_{i=1}^{\infty} i\pi_i$, the average number of packets in buffer is $L_q = L_s - (1 - \pi_0)$ and the average waiting time of each packet is

$$T_q = \frac{L_q}{\lambda}$$

3.2 Drop Probability and Go Through Delay Analysis

In the finite buffer case, say has space for only K packets, define the tail probability $P_k^{(t)} = \sum_{j=k}^{\infty} P_j = 1 - \sum_{j=-1}^{k-1} P_j$, so the transition matrix becomes

$$\mathbf{P} = \begin{pmatrix} P_0 + P_{-1} & P_{-1} & 0 & \cdots & 0 \\ P_1 & P_0 & P_{-1} & \cdots & 0 \\ P_2 & P_1 & P_0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ P_{K-1} & P_{K-2} & P_{K-3} & \cdots & P_{-1} \\ P_K^{(t)} & P_{K-1}^{(t)} & P_{K-2}^{(t)} & \cdots & P_0^{(t)} \end{pmatrix}$$

, and $\boldsymbol{\pi} = [\pi_0\ \pi_1 \cdots\ \pi_K]^T$ is vector of stationary distribution.

The stationarity distribution can be found as follows:

Choose $\pi_0 > 0$, say $\pi_0 = 1$. Compute $\pi_1, \pi_2, \ldots, \pi_K$ iteratively,

$$\begin{aligned} \pi_1 &= \frac{(1 - P_0 - P_{-1})\pi_0}{P_{-1}} \\ \pi_k &= \frac{\pi_{k-1} - \sum_{r=0}^{k-1} \pi_r P_{k-r-1}}{P_{-1}}, \quad 2 \le k < K \\ \pi_K &= \frac{\pi_{K-1} - \sum_{r=0}^{K-2} \pi_r P_{K-r-1} - \pi_{K-1} P_0^{(t)}}{P_{-1}} \end{aligned} \tag{6}$$

Then renormalize to get the sum of the probabilities $\pi_0 + \pi_1 + \cdots + \pi_K = 1$.

We also have $\mu = -\sum_{i=-1}^{K} iP_i$. Since the buffer is finite, common sense indicates that the system is always stationary, whether $\mu > 0, \mu = 0$ or $\mu < 0$. In case of a finite buffer size, the new arrival will be dropped when the buffer is full.

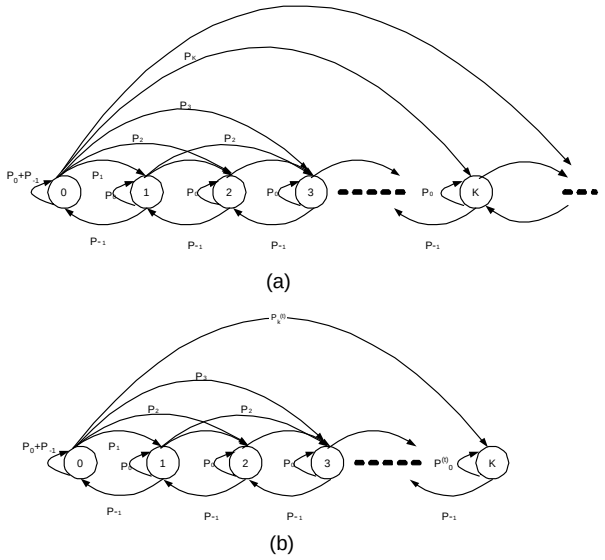

Figure 2: Markov chain model(a) infinite buffer case, (b) finite buffer case

The probability of packet being dropped is

$$\begin{aligned} P_{drop} &= \pi_K \left(P_0^{(t)} - P_0\right) + \pi_{K-1} \left(P_1^{(t)} - P_1\right) + \cdots \\ &+ \pi_0 \left(P_K^{(t)} - P_K\right) \\ &= \sum_{i=0}^{K} \pi_i \left(P_{K-i}^{(t)} - P_{K-i}\right) \end{aligned} \tag{7}$$

Moreover, defining delay as the delay of the packets that actually get through. The average number of packets in system is $L_s = \sum_{i=0}^{K} i\pi_i$

The average number of packets in buffer is $L_q = L_s - (1 - \pi_0)$ and the average go through delay of each packet is

$$T_q = \frac{L_q}{\lambda(1 - p_{drop})}$$

If the buffer size increases, the fraction of customers that get dropped decreases and the average go through delay increase. If $\mu > 0$, buffer size gets large (to infinite), drop probability goes to zero, while average delay goes to some constant. If $\mu < 0$, buffer gets large, drop probability goes to $1 - P_{ST}/\alpha$ and delay goes to infinite, as fast as K/P_{ST}. If $\mu = 0$, buffer gets large, drop probability goes to zero, and delay goes to infinite, as fast as $\frac{1}{2}\frac{K}{P_{ST}}$.

4. PERFORMANCE ANALYSIS USING M/G/1 QUEUEING MODEL

At the previous section, we use discrete model to analyze the system. In this section, we will use the continuous model to model the system. Let us consider a queueing system immediately after a customer has departed and service is about to commence on the next customer in queue, with service times assumed to be independently and identically distributed random variables with an arbitrary probability distribution. We denote the service time by b, and the cumulative distribution function by $B(t)$. The arrival process is Poisson with parameter λ. The imbedded stochastic process $X(t_i)$, where X denotes the number in the system and

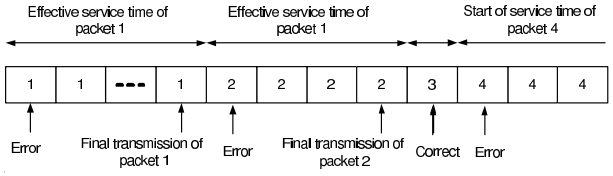

Figure 3: Illustration of the effective service time of packet in the system. For example, packet 1 has an effective service time of 4 because there were 3 errors in the first three times attempt to transmit it, but no error in the forth attempt

$t_1, t_2, \ldots$ are the successive times of completion time of the ith customer, can be shown to be Markovian as follows [2].

$$Pr\{X_{n+1} = j | X_n = i\} = \quad (8)$$
$$\begin{cases} \int_0^\infty \frac{e^{-\lambda t}(\lambda t)^{j-i+1}}{(j-i+1)!} dB(t) & (j \geq i-1, i \geq 1), \\ 0 & (j < i-1, i \geq 1). \end{cases}$$

4.1 Delay Performance Analysis

A given packet transmitted might be retransmit due to errors (see Figure 3). It follows that the time interval between the start of the first transmission and the last transmission of a given packet is $k\tau$ with probability $P_{ST}P_{FT}^{k-1}$. The transmitter queue behaves like an M/G/1 queue with service time distribution given by

$$P\{b = k\tau\} = P_{ST}P_{FT}^{k-1} = (1-P)P^{k-1}, \;\; k = 1, 2, \ldots$$

where $P \triangleq P_{FT} = 1 - P_{ST}$.

The first two moments of the service time are

$$\overline{b} = \sum_{k=0}^{\infty} k\tau(1-P)P^{k-1} = \tau(1-P)\sum_{k=0}^{\infty} kP^{k-1} = \frac{\tau}{1-P}$$

$$\overline{b^2} = \sum_{k=0}^{\infty} k^2\tau^2(1-P)P^{k-1} = \tau^2(1-P)\sum_{k=0}^{\infty} k^2P^{k-1} = \tau^2\frac{1+P}{(1-P)^2}$$

The P-K formula gives the average packet time in queue

$$W = \frac{\lambda\overline{b^2}}{2(1-\lambda\overline{b})} \quad (9)$$

We observe that, the average service time is constant (depends on P), the average waiting time increase while the packets arrival rate increase, when the packet arrival rate increase close to the service rate, the average waiting time goes to infinity. Hence, the system is stable when $(1-\lambda\overline{b}) > 0$, that is $\lambda < 1/\overline{b}$ (the packet arrival rate is less than the average service rate). The average delay time of each packet is

$$T = \overline{b} + W \quad (10)$$

4.2 Departure-Point Steady-State System-Size Probability

We let π_n represent the probability of n packets in the system at a departure point (a point of time just after a customer has completed service) after steady state is reached. The imbedded stochastic process at departure points is a Markov chain, the transition probability matrix is

$$\mathbf{P} = \{p_{ij}\}$$

where

$$\begin{aligned} p_{ij} &= Pr\{\text{system size after a departure point is } j | \\ &\quad \text{system size after previous departure was } i\} \\ &= Pr\{X_{n+1} = j | X_n = i\} \quad (11) \end{aligned}$$

Simplification results on defining

$$\begin{aligned} k_n &= Pr\{n\text{arrivals during a service time}\} \quad (12) \\ &= \int_0^\infty \frac{e^{-\lambda t}(\lambda t)^n}{(n)!} dB(t) \end{aligned}$$

so that p_{ij} can be seen to equal k_{j-i+1} and

$$\mathbf{P} = \begin{pmatrix} k_0 & k_0 & 0 & 0 & 0 & \cdots \\ k_1 & k_1 & k_0 & 0 & 0 & \cdots \\ k_2 & k_1 & k_0 & k_0 & 0 & \cdots \\ k_3 & k_3 & k_2 & k_1 & k_0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & & \ddots \end{pmatrix} \quad (13)$$

Assume steady state is achievable, the steady-state probability vector $\boldsymbol{\pi} = \{\pi_n\}$, can be found as the solution to the stationary equation

$$\mathbf{P}\boldsymbol{\pi}^T = \boldsymbol{\pi}^T$$

This yields

$$\pi_i = \pi_0\, k_i + \sum_{j=1}^{i+1} \pi_j\, k_{i-j+1} \quad (i = 1, 2, \ldots) \quad (14)$$

Now define the generating functions

$$\Pi(z) = \sum_{i=0}^{\infty} \pi_i z^i \quad \text{and} \quad K(z) = \sum_{i=0}^{\infty} k_i z^i \;\; (|z| < 1)$$

Then multiplying (14) by z^i, summing over i, and solving for $\Pi(z)$

$$\Pi(z) = \frac{\pi_0(1-z)K(z)}{K(z) - z}$$

Using the fact $\Pi(1) = 1$, along with L'Hôpital's rule, and realizing that $K(1) = 1$ and $K'(1) = \frac{\lambda}{\mu}$, we find that

$$\pi_0 = 1 - \rho \quad (\rho \equiv \lambda E[\text{service time}])$$

Hence

$$\Pi(z) = \frac{(1-\rho)(1-z)K(z)}{K(z) - z} \quad (15)$$

Define the throughput as the average number of the successfully transmitted data packets per period,

$$R = \sum_{i=1}^{\infty} \pi_i \cdot P_{ST} = P_{ST}\,(1 - \pi_0) \quad (16)$$

4.3 Finite M/G/1 Queues

We use M/G/1/K system to study the finite buffer size case, where $1 \leq K \leq \infty$. Two major performance measures in the M/G/1/K system are the go through delay D (mean response time[8]) of a message that is accepted in the system, and the drop probability P_d that an arrival message is droped/blocked because the system is full when it arrivals.

We define $\rho = \lambda b$ as the traffic load of the system, where $\overline{b}$ is mean for the service time of a message. The carried load

of the system is $\rho' = \gamma\overline{b} = \rho(1 - P_d)$, which is the fraction of the time that the service is busy. From Little's theorem applied to those message accepted in the system, we have

$$L = \gamma D \tag{17}$$

The analysis of the finite-capacity M/G/1/K queue proceeds in a similar way to that of the infinite buffer size case. The PK formulas will not hold because the expected number of arrival during a service period must be conditioned on the system size. The single-step transition matrix must here be truncated at $K-1$, so that,

$$\mathbf{P} = \begin{pmatrix} k_0 & k_0 & 0 & \cdots & 0 \\ k_1 & k_1 & k_0 & \cdots & 0 \\ k_2 & k_2 & k_1 & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ 1 - \sum_{n=0}^{K-2} k_n & 1 - \sum_{n=0}^{K-2} k_n & 1 - \sum_{n=0}^{K-3} k_n & \cdots & 1 - k_0 \end{pmatrix}$$

implies that the stationary equation is

$$\pi_{i+1} = \begin{cases} \pi_0\, k_i + \sum_{j=1}^{i} \pi_j\, k_{i-j+1} & i = 1, 2, \ldots, K-2 \\ 1 - \sum_{j=0}^{K-2} \pi_j & i = K-1 \end{cases} \tag{18}$$

Equation 18 provide K independent equations for K unknowns (π_k, $0 \le k \le K-1$).

An efficient algorithm for computing π_k can be given in terms of

$$\pi'_k \triangleq \frac{\pi_k}{\pi_0} \quad 0 \le k \le K \tag{19}$$

It is easy to see form 18 that $\{\pi'_k; 0 \le k \le K-1\}$ can be recursively calculated as follows: $\pi'_0 = 1$

$$\pi'_{k+1} = \frac{1}{k_0}\left(\pi'_k - \sum_{j=1}^{k} \pi'_j k_{k-j+1} - k_k\right) \quad 0 \le k \le K-1$$

and π_0 is found from $\sum_{k=0}^{K-1} \pi_k = 1$ as

$$\pi_0 = \left(\sum_{k=0}^{K-1} \pi'_k\right)^{-1}$$

Thus we get π_k from 19. The computational complexity of this algorithm is of order $O(k^2)$. Note that the above form for the set of linear equations for π'_k is called an *upper Hessenberg matrix*, and is suitable for numerical computation.

The mean of the number of packets in the system at an arbitrary time is thus given by

$$L = \sum_{i=0}^{K} iP_i = \frac{\sum_{k=1}^{K-1} k\pi_k}{\pi_0 + \rho} + K(1 - \frac{1}{\pi_0 + \rho}) \tag{20}$$

.

From 17, the go through delay is

$$D = \frac{1}{\lambda}\left[\sum_{k=1}^{K-1} k\pi_k + K(\pi_0 + \rho - 1)\right]$$

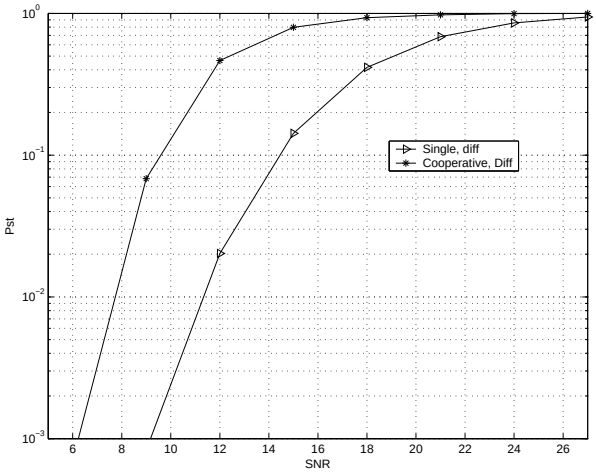

Figure 4: Probability of packet successfully transmission vs. SNR

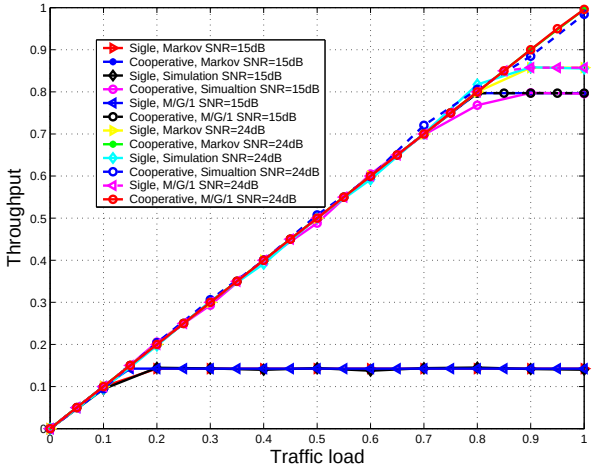

Figure 5: Throughput vs. traffic load (infinite buffer size)

5. SIMULATION RESULTS

To observe the performance of the DSTBC for cooperative relays method, we compared it with the single relay method through simulation. In our simulation, the source node's buffer is feeded by Poisson sources with density λ. The simulation carried under three scenarios: 1) $K = 2$, 2) $K = 5$ and 3) $K = 10$. The hop number $L = 3$. The packet length $Len = 128$. Under each scenario, both methods work on same SNR environment.

Figure 4 shows the probability of packet successful transmission vs. SNR. The diversity gain of the cooperative relays at P_{ST} of 0.9 is about 9 dB better than a single relay scheme.

The throughput performance is shown in Figure 5 as a function of the traffic load when buffer size is infinite. The throughput equals to traffic load when the traffic load less than the system capacity ($\mu > 0$), then the throughput equals to the system capacity. We also note that the higher SNR, the higher throughput. The cooperative one has the higher throughput. The delay performance is shown in Fig-

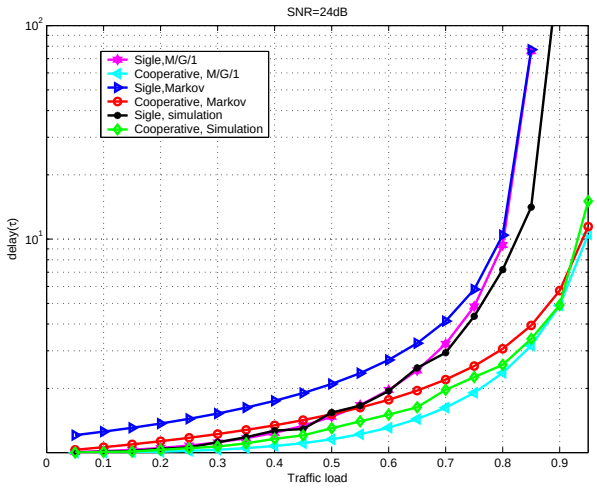

Figure 6: Delay vs. traffic load (infinite buffer size)

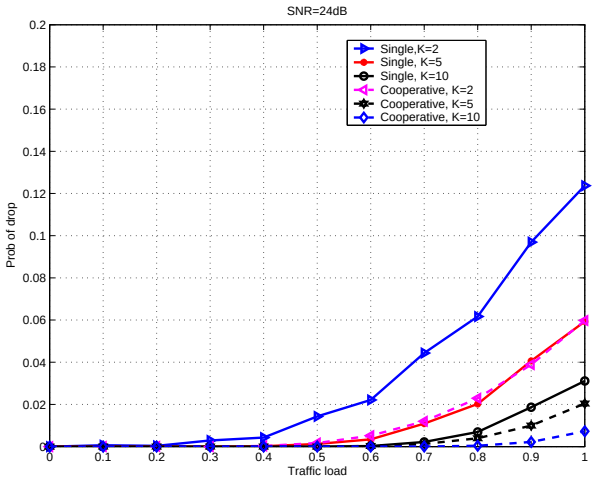

Figure 7: Drop probability vs. traffic load (K=2,5,10)

ure 6 as a function of the traffic load when buffer size is infinite (SNR=24dB). The delay goes higher when traffic load increase. When the traffic load reach the system capacity, delay goes to infinity. The cooperative one has the smaller delay. Figure 7 shows the drop probability versus traffic load (K=2, 5 and 10). The probability of drop increases when traffic load increases. The probability of drop decreases when buffer size increases. The simulation results demonstrate that the cooperative scheme has smaller drop probability than the traditional one. Figure 8 shows the go through delay versus traffic load (K=2, 5 and 10). The go through delay increases when traffic load increases. It also increase when buffer size increases. The simulation results demonstrate that the cooperative scheme has smaller drop probability than the traditional one.

6. CONCLUSION

In this paper, we investigate the impact of buffer size on the network performance of the multi-hop sensor networks using Markov chain model and M/G/1 queueing system.

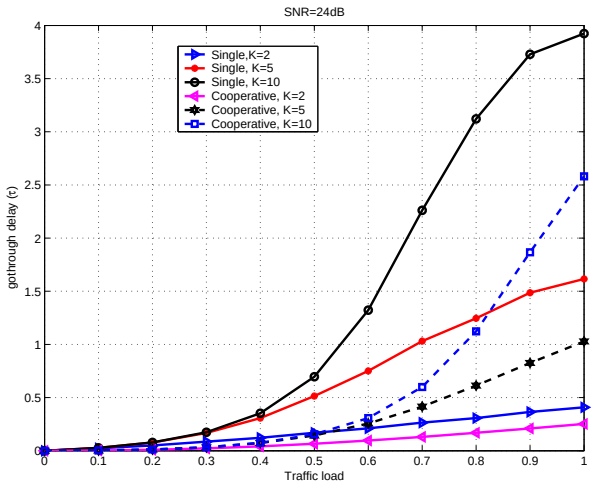

Figure 8: Go through delay vs. traffic load (K=2,5,10)

They are used to model the network performance and therefore the system capacity is studied and the throughput and end-to-end delay are analyzed under infinite buffer size situation. When buffer size is limited, the go through delay and the drop probability are also discussed. The analytical and simulation results are compared and indicate that the buffer size has significant impact on system performance.

7. REFERENCES

[1] M. Dohler, A. Gkelias, and A. H. Aghvami. Capacity of distributed phy-layer sensor networks. *Vehicular Technology, IEEE Transactions on*, 55:622–639, March 2006.

[2] D. Gross and C. M. Harris. *Fundamentals of queueing theory*. A Wiley-Interscience Publishing, New York, NY, 1998.

[3] J. Keilson. *Markov chain models-rarity and exponentiality*. Springer-Verlag, New York, NY, 1979.

[4] L. Liu and H. Ge. Space-time coding for wireless sensor networks with cooperative routing diversity. In *IEEE. Proc. Asilomar Conf. on Signal, System and Computers*, volume 1, pages 1271–1275, Pacific Grove, CA, Nov. 2004.

[5] L. Liu, H. Ge, and T. J. Ott. Differential STBC Scheme for Cooperative Relays in Multi-hop Sensor Networks. In *Proc. Milcom*, Atlantic City, NJ, Oct 2005.

[6] V. I. Morgenshtern, H. Bolcskei, and R. U. Nabar. Distributed orthogonalization in large interference relay networks. In *Proc. IEEE ITIS*, pages 1211–1215, Sept 2005.

[7] F. Ng and X. Li. Cooperative stbc-ofdm transmissions with imperfect synchronization in time and frequency. In *the 39th Asilomar Conference on Signals, Systems and Computers*, Pacific grove, CA, 2005.

[8] H. Takagi. *Queueing analysis A foundation of Performance evaluation*. North Holland Publishing Company, New York, NY, 1993.

[9] V. Tarokh and H. Jafarkhani. A differential detection scheme for transmit diversity. *IEEE J. on Selected Areas in Communications*, 18:1451–1458, July 2000.