Sensor Network with Multiple Mobile Access Points

Parvathinathan Venkitasubramaniam, Qing Zhao and Lang Tong
School of Electrical and Computer Engineering
Cornell University, Ithaca, NY 14853, USA
Email: pv45@cornell.edu,{qzhao,ltong}@ece.cornell.edu

Abstract

We consider sensor networks with mobile access points where data at sensor nodes are collected by multiple mobile access points. Using throughput and energy efficiency as performance measures, we address the optimal coverage areas of and the cooperation among the mobile access points. We show that when the mobile access points do not cooperate in demodulation, disjoint coverage areas are optimal for throughput while completely overlapped coverage areas are optimal for energy efficiency. When the mobile access points decode their received packets jointly, the optimal configuration appears to have a phase transition. Specifically, in order to maximize throughput, the coverage areas of the mobile access points should be completely overlapped when SNR is smaller than a threshold and disjoint otherwise.

Length: Regular Paper.

Keywords: Sensor Network. Mobile Access Point. Throughput. Energy Efficiency.

I. Introduction

A. Sensor Networks with Mobile Access Points

Sensor network with mobile access points (SENMA) is an architecture proposed for low-power large-scale sensor networks [1]. As shown in Figure 1, SENMA consists of two types of nodes: sensors and mobile access points. Sensors are low power and low cost nodes that are limited in processing and communication capability. In contrast, mobile access points are equipped with powerful processors and sophisticated transceivers, capable of traversing the sensor field with carefully designed trajectory. Examples of mobile access points include manned/unmanned aerial and ground vehicles and specially designed light nodes that can hop around in the network. They may form a small ad hoc network and perform collaborative data collection and post processing adding a new dimension in the space-time domain.

In SENMA, sensors communicate directly with the mobile access points. This avoids much of the overhead associated with medium access control and routing and effectively shifts the critical network network operations away from the sensor nodes to the more powerful APs. The mobility of the APs adds a significant dimension to the data collection and provides scope for further optimization of network performance by an appropriate choice of flying pattern and cooperative reception.

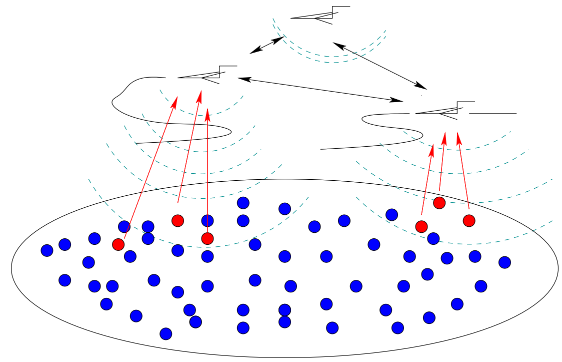

Fig. 1. Sensor Networks with Mobile Access

B. Summary of Results

The performance of sensor networks with a single mobile AP is well discussed in [2]. In this paper, we study the coverage areas of and the interaction among multiple mobile access points in a distributed multiple access scenario. As illustrated in Figure 2, a mobile access point (AP) activates a segment of the network in its vicinity at a given instant of time. All sensors in the coverage area of the AP "wake up" upon activation and start data transmission according to a certain protocol. We seek answers to the following questions: should the coverage areas of the mobile access points overlap? is there an optimal fraction of overlapping for a given SNR? should the mobile access points cooperate in demodulation?

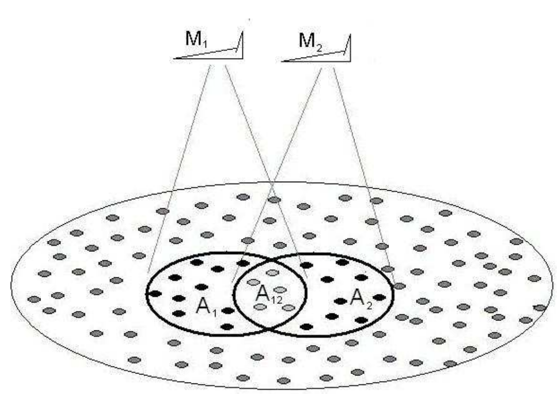

Fig. 2. SENMA with two Mobile Access Points

The analysis is conducted using a packet framework and answers are derived under two performance measures: throughput defined as the average number of successfully received packets per time slot and efficiency defined as the average number of successfully received packets per transmission. The former is a measure of the network latency while the latter a measure of energy efficiency. When two mobile access points decode their received packets separately, we show that the optimal configuration under throughput is for the mobile access points to have disjoint coverage areas. Under the metric of efficiency, however, the coverage areas of the mobile access points should completely overlap.

When the packets received by the mobile access points are decoded jointly, maximum ratio combining can be used to improve the reception of the packets transmitted by sensors in the overlap of the coverage areas (region A_{12} in Figure 2). In this case, we observe that the optimal configuration under throughput undergoes a phase transition as SNR increases; there exists an SNR threshold beyond which the optimal coverage areas of the mobile access points change from being completely overlapped to being disjoint. These findings provide important insights into network design. An information-theoretic analysis of similar network configurations of SENMA has been presented in [3], [4]. Our conclusions with regard to flying patterns are similar in nature to the inferences drawn in [3].

II. System Model

We consider a network where sensors are randomly distributed over a field. It is assumed that every sensor has data to transmit. The network is assumed to operate in time division duplex (TDD) mode. Time is slotted into intervals of equal length that is equal to the transmission time of a packet. At the beginning of every slot, the AP transmits a beacon, which is used by sensors to gain synchronization. We assume that beacons transmitted by different APs are synchronous and indistinguishable. Each activated sensor, upon receiving a beacon, transmits its information with a constant probability p. This probability is a function of the channel state distribution and size of the network and can be optimized to maximize the throughput or efficiency as desired.

A. Channel Model

In this section, we describe the basic channel model used in the analysis of the network. The mobile APs are assumed to fly at a height d above the network. We assume that the radial distances of the sensors are negligible compared to d. The propagation channel gain between the ith sensor and the AP during slot t is given by

$$\gamma = \frac{|R_{it}|^2}{d^2} \tag{1}$$

where R_{it} is a complex Gaussian random variable. The channel state γ is independent and identically distributed across sensors,across slots and from one AP to another. All sensor are assumed to transmit using the same transmit power P_T. Since d is a constant for all sensors, we shall henceforth incorporate it into the transmit power of the sensor.

B. Data Reception Model

In this section, we shall describe the reception model of a single mobile AP. Collaborative reception of multiple APs will be discussed in section IV-A. We assume the physical layer is based on direct sequence spread spectrum communication with spreading gain N. There is a pool of N orthogonal codes, and each transmitting sensor randomly picks a code for transmission. The receiver performs matched filtering on each code to demodulate the received data. The reception of a packet is successful if the received signal to interference and noise ratio (SINR) is greater than a threshold β. In slot t, if K_j sensors transmit using the j^{th} spreading code and their channel states are given by $(\gamma_{j_1}^{(t)}, \cdots, \gamma_{j_{K_j}}^{(t)})$, then the criterion for successful reception of sensor i is well-approximated [5] by

$$\frac{P_T \gamma_{j_i}^{(t)}}{\sigma^2 + \sum_{k=1,k\neq i}^{K_j} P_T \gamma_{j_k}^{(t)}} > \beta,$$

where σ^2 is the variance of the background noise. It is assumed that $\beta > 1$.

C. Performance Metrics

In order to compare the performance of SENMA for different configurations, two metrics are used - throughput and efficiency. The throughput of the network is given by the average number of packets successfully received per slot. The efficiency of the network is given by the average number of packets successfully received per transmission. For the comparison of different configurations, the probability of transmission is optimized to maximize the required metric. Let p denote the probability of transmission for a sensor. Let C_k denote the throughput per slot when k sensors transmit. The maximum throughput and efficiency are given by

$$\lambda = \max_p \sum_{k=1}^{n} \binom{n}{k} p^k (1-p)^{n-k} C_k \tag{2}$$

$$\eta = \max_p \frac{\sum_{k=1}^{n} \binom{n}{k} p^k (1-p)^{n-k} C_k}{np} \tag{3}$$

where n is the number of activated sensors.

III. SENMA with Non-cooperative Mobile APs

In this section we shall analyze the performance of SENMA with two non-cooperating mobile APs. Consider the network as shown in Figure 2. The mobile AP M_1 can received packets from transmitting sensors in A_1 and A_{12}, whereas M_2 can receive packets from transmitting sensors in A_2 and A_{12}. It is assumed that the beacons transmitted by the MAPs are synchronized and indistinguishable. The sensors are therefore unaware of their location, and hence the probability of transmission p is a constant, optimized to maximize the performance metric. The sensors are uniformly distributed across the network and the number of sensors in the area of activation of an AP is assumed to be a constant n. Hence, if the fraction of overlap is given by $\frac{A_{12}}{A_1} = \frac{A_{12}}{A_2} = \rho$, the number of sensors in A_1, A_2, and A_{12} are given by $(1-\rho)n, (1-\rho)n$ and ρn respectively. We point out that the results obtained below also apply to cases of randomly distributed n. This deterministic setup is for the ease of presentation.

A. Performance Comparison

We shall now compare the performance of the network under three configurations - no overlap ($\rho = 0$) , complete overlap ($\rho = 1$) and partial overlap ($0 < \rho < 1$).

1) No Overlap: In the case of no overlap, the two mobile APs activate independent regions of the network. Since, it is assumed that channel state is $i.i.d$ across sensors and time slots, the throughput of the system is twice the throughput of a network with one AP. Let $P_k(P_T, \rho = 0)$ [6] denote the average probability of successful reception of a packet when k sensors transmit with transmit power P_T. The throughput and efficiency are given by

$$\lambda(p, \rho = 0) = 2\sum_{k=1}^{n} \binom{n}{k} p^k (1-p)^{n-k} k P_k(P_T, 0) \quad (4)$$

$$\eta(p, \rho = 0) = \frac{\sum_{k=1}^{n} \binom{n}{k} p^k (1-p)^{n-k} k P_k(P_T, 0)}{np} \quad (5)$$

$$P_k(P_T, 0) = \frac{e^{-\beta\sigma^2/P_T}}{(1+\beta)^{k-1}} \quad (6)$$

where p is the probability of transmission.

2) Complete Overlap: The mobile APs activate the same region of the network, and each transmitting sensor can be received by both the APs. If we let $P_k(P_T, \rho = 1)$ denote the probability that given k sensors transmit, a sensor is successfully received at atleast one AP, the throughput and efficiency can be similarly given by

$$\lambda(p, 1) = \sum_{k=1}^{n} \binom{n}{k} p^k (1-p)^{n-k} k P_k(P_T, 1) \quad (7)$$

$$\eta(p, 1) = \frac{\sum_{k=1}^{n} \binom{n}{k} p^k (1-p)^{n-k} k P_k(P_T, 1)}{np} \quad (8)$$

$$P_k(P_T, 1) = 2P_k(P_T, 0) - (P_k(P_T, 0))^2 \quad (9)$$

where p is the probability of transmission, which can be optimized depending on the metric of performance required.

The following theorem characterizes the optimal fraction of overlap for the different performance metrics discussed.

Theorem 1: For any given P_T,

i) $\max_p \lambda(p, \rho) \leq \max_p \lambda(p, 0)$
ii) $\max_p \eta(p, \rho) = 2P_1(P_T, 0) - \rho(P_1(P_T, 0))^2/(2-\rho)$
iii) $\max_p \eta(p, \rho) \leq \max_p \eta(p, 1)$.

Proof: i) Consider the network as shown in figure 2. As stated before, let the number of sensors in A_1, A_{12}, A_2 be equal to $n1 = (1-\rho)n, n2 = \rho n, n_3 = n_1$ respectively. Since it is assumed that beacons are synchronous and indistinguishable,

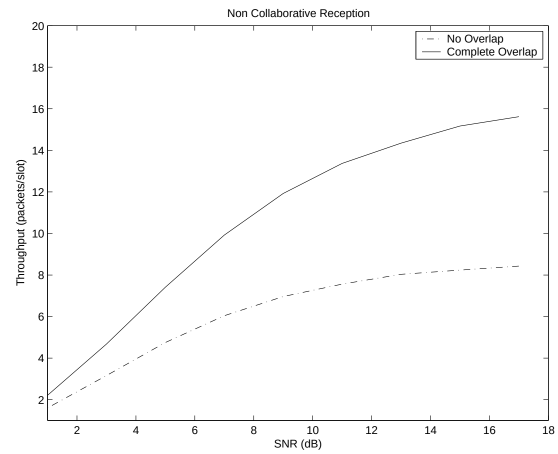

Fig. 3. Throughput of SENMA with two non-cooperative Mobile Access Points

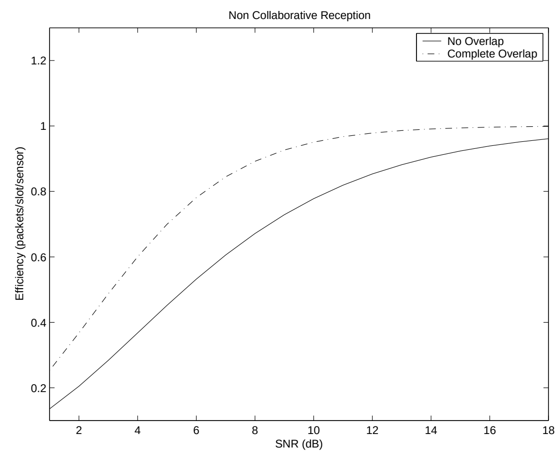

Fig. 4. Efficiency of SENMA with two non-cooperative Mobile Access Points

the probability of transmission is a constant p. The throughput of the network with fraction of overlap ρ is given by

$$\lambda(p, \rho) = \sum_{k_1=0}^{n_1} \sum_{k_2=0}^{n_2} \sum_{k_3=0}^{n_3} \binom{n_1}{k_1}\binom{n_2}{k_2}\binom{n_3}{k_3} p^{k_1+k_2+k_3} (1-p)^{n_1+n_3+n_2-k_1-k_2-k_3} \left[k_1 P_{k_1+k_2} + k_3 P_{k_2+k_3} + k_2\left(P_{k_1+k_2}(P_T, 0) + P_{k_2+k_3} - P_{k_1+k_2}P_{k_2+k_3}\right)\right] \quad (10)$$

In the above equation, we have used P_k to denote $P_k(P_T, 0)$ for ease of presentation. Equation (10) can be obtained from the fact that, sensors transmitting in each region are independent. Sensors in A_1 and A_2 (k_1 and k_3 respectively) are received by only one AP, while sensors in A_{12} (k_2) are received by both APs. The above expression can be rewritten as

$$\lambda(p, \rho) = 2\sum_{k_1=0}^{n_1} \sum_{k_2=0}^{n_2} p^{k_1+k_2} (1-p)^{n_1+n_2-k_1-k_2} (k_1+k_2) P_{k_1+k_2}(P_T, 0) - \alpha, \quad \alpha \geq 0$$

$$
\begin{aligned}
&= 2\sum_{k=0}^{n_1+n_2} p^k(1-p)^{n_1+n_2-k}(k)P_k(P_T,0) - \alpha \\
&= 2\sum_{k=0}^{n} p^k(1-p)^{n-k}kP_k(P_T,0) - \alpha \\
&\leq \lambda(p,0)
\end{aligned}
$$

From the above equations, it is clear that$\lambda(p,0)$ is greater than $\lambda(p,\rho)$ for any given p. Therefore, i) is true.

ii)Since the transmissions in each orthogonal code are independent, the throughput scales linearly with the spreading gain, and it is sufficient to consider the efficiency for $N=1$. Assuming that $\beta > 1$, at most one packet can be successfully received per orthogonal code [5]. Therefore the efficiency is maximized when probability of interference in minimized $i.e.$ when the probability of transmission is close to zero. In other words,

$$
\begin{aligned}
& \max_p \eta(p,\rho) \\
&= \lim_{p\to 0} \frac{\lambda(p,\rho)}{(2n_1+n_2)p} \\
&= \lim_{p\to 0} \frac{2n_1 p P_1(P_T,0) + n_2 p P_1(P_T,1)}{(2n_1+n_2)p} \\
&= \frac{2(1-\rho)P_1(P_T,0) + \rho 2P_1(P_T,0) - \rho(P_1(P_T,0))^2}{(2-\rho)} \\
&= \frac{2P_1(P_T,0) - \rho(P_1(P_T,0))^2}{2-\rho}
\end{aligned}
$$

iii) It is easy to see that the expression for $\max_p \eta(p,\rho)$ is non-decreasing. Hence the maximum occurs at $\rho = 1$.

□□□

From the above theorem, it is clear that the optimal configuration to maximize the throughput requires the two mobile APs to activate independent regions, whereas the configuration needed to maximize the efficiency requires the APs to activate the same region. The plots in Figure 3 and 4 verify the above facts. These results also apply to a general distribution of sensors in a field, and not only a fixed number of sensors n in the activated region. This is proved in the following corollary.

Corollary 1: Let $q(n,A)$ be the probability that an area A in the network has n sensors. Let $\bar{\lambda}(p,\rho)$ represent the average throughput of a network with fraction of overlap ρ and number of sensors distributed according to q. Then, for any P_T, $\bar{\lambda}(p,\rho) \leq \bar{\lambda}(p,0)$.

Proof: Let $\lambda_n(p,\rho)$ denote the throughput of a system with transmission probability p, fraction of overlap ρ and n sensors in the activated region. The average throughput of a network as shown in figure 2 is given by

$$
\bar{\lambda}(p,\rho) = \sum_{n_1}\sum_{n_2}\sum_{n_3} q(n_1,A_1)q(n_2,A_{12})q(n_3,A_2)\lambda(p,\rho)
$$

where $\lambda(p,\rho)$ is as given in equation 10. We can rewrite 10 as

$$
\begin{aligned}
&\lambda(p,\rho) = \\
&\sum_{k_1=0}^{n_1}\sum_{k_2=0}^{n_2} p^{k_1+k_2}(1-p)^{n_1+n_2-k_1-k_2}(k_1+k_2)P_{k_1+k_2}(P_T,0) + \\
&\sum_{k_3=0}^{n_3}\sum_{k_2=0}^{n_2} p^{k_3+k_2}(1-p)^{n_3+n_2-k_1-k_2}(k_3+k_2)P_{k_3+k_2}(P_T,0) - \alpha \\
&\leq \tfrac{1}{2}\left(\lambda_{n_1+n_2}(0,\rho) + \lambda_{n_3+n_2}(0,\rho)\right)
\end{aligned}
$$

Therefore,

$$
\begin{aligned}
\bar{\lambda}(p,\rho) &= \sum_{n_1}\sum_{n_2}\sum_{n_3} q(n_1,A_1)q(n_2,A_{12})q(n_3,A_2)\lambda(p,\rho) \\
&\leq \sum_{n_1}\sum_{n_2}\sum_{n_3} q(n_1,A_1)q(n_2,A_{12})q(n_3,A_2) \\
&\quad \frac{1}{2}\left(\lambda_{n_1+n_2}(0,\rho) + \lambda_{n_3+n_2}(0,\rho)\right) \\
&\stackrel{a}{=} 2\sum_{n_1}\sum_{n_2} q(n_1,A_1)q(n_2,A_{12})\frac{\lambda_{n_1+n_2}(0,\rho)}{2} \\
&= \sum_{n} q(n, A_1+A_{12})\lambda_n(0,\rho) \\
&= \bar{\lambda}(p,0)
\end{aligned}
$$

The equality a is because A_1 and A_2 are equal in area and $A_1 + A_{12}$ is equal to the activation region of one AP. The corollary therefore justifies the claims for a random distribution of sensors across the network.

□□□

IV. SENMA WITH CO-OPERATIVE MOBILE APS

In this section, we shall numerically analyze the performance of SENMA with mobile APs that co-operate with each other in reception. In reference to figure 2, the mobile APs can co-operate in the reception of packets from sensors in A_{12}.

A. Reception Model

The collaborative reception implemented in this paper is in the form of maximum ratio combining (MRC). Each transmitting sensor transmits pilots in the packet, which are used by the APs to estimate the channel gain between the sensor and the AP. It is assumed that there are a large number of pilots, and each sensor randomly chooses a pilot for transmission. The probability that two sensors simultaneously transmit the same pilots is negligible. If R_{i1} and R_{i2} represent the complex gains for sensor i at the two APs, then the SINR at the output of the MRC is given by [7]

$$
\gamma_i = \frac{|R_{i1}R_{i1}^* + R_{i2}R_{i2}^*|^2}{\left|R_{i1}^*\left(n_1 + \sum_{j\neq i} R_{j1}\right) + R_{i2}^*\left(n_2 + \sum_{j\neq i} R_{j2}\right)\right|^2} \tag{11}
$$

The packet is successfully received if $\gamma_i > \beta$.

B. Performance Comparison

Since, collaboration is not possible when there is no overlap in the activation regions, the throughput and efficiency of a network with no overlap is the same as given by equations (4) and (5).

1) Complete Overlap: As discussed in the previous section, the throughput and efficiency of a network with complete overlap can be given by

$$\lambda^c(p,1) = \sum_{k=1}^{n} \binom{n}{k} p^k (1-p)^{n-k} k P_k^c(P_T,1) \quad (12)$$

$$\eta^c(p,1) = \frac{\lambda(p,1)}{np} \quad (13)$$

where $P_k^c(\cdot,\cdot)$ is the average probability of success of a sensor through coherent detection, given k sensors transmit. For the model discussed in the previous section, the expression for $P_k^c(\cdot,\cdot)$ can be given by [8]:

$$P_k^c(P_T,1) = 1 - \left(\frac{\beta}{\beta+\Gamma_k}\right)^2 \quad (14)$$

$$\Gamma_k = \frac{1}{\frac{\sigma^2}{P_T} + k - 1} \quad (15)$$

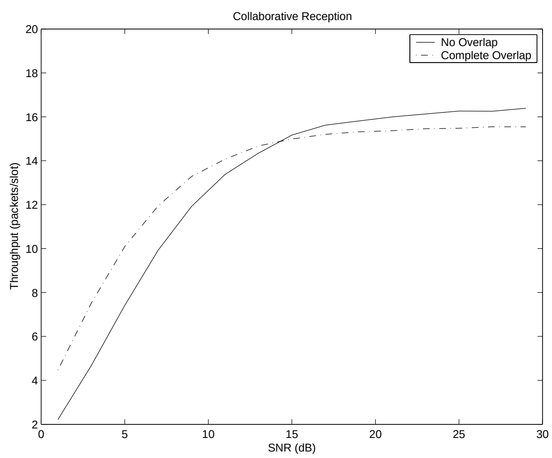

Fig. 5. Throughput of SENMA with two cooperative Mobile Access Points

The comparison of throughput and efficiency for the two cases is plotted with respect to SNR in figure 5 and 7. It is evident from the figure that a phase transition occurs at a particular SNR, below which the completely overlapped network has a higher maximum throughput, and above which the zero overlap configuration yields a higher throughput. It however remains to be seen, if it is possible to obtain a higher throughput through partial overlap ($0 < \rho < 1$). The following theorem provides an insight on the performance of such topologies¿

Theorem 2: Let $\lambda^c(p,\rho)$ be the throughput of a system with fraction of overlap ρ and probability of transmission p. If sensors in the two non-overlapping regions (A_1 and A_2) are assumed to have symmetric probabilities of transmission, then for any probability of transmission p

$$\lambda^c(p,\rho) \le \rho \max_p \lambda^c(p,1) + \max_p (1-\rho)\lambda^c(p,0) \quad (16)$$

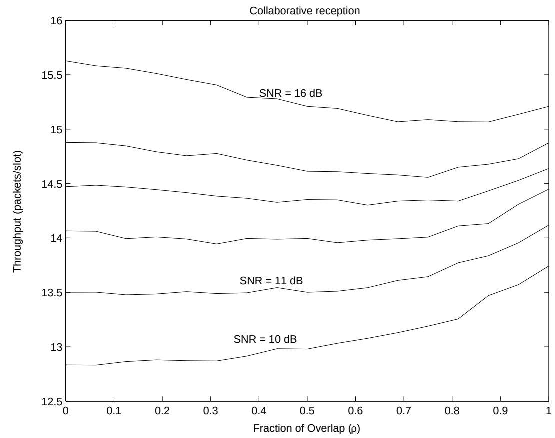

Fig. 6. Throughput of SENMA with two cooperative Mobile Access Points and partial overlap

Proof: Consider the network as shown in Figure 2. The symmetry condition requires sensors in A_1 and A_2 to have symmetric probabilities of transmission. In other words, if k sensors in A_1 decide to transmit, an equal number of sensors in A_2 would also transmit. Therefore, the network can now be divided into two sections, $A_1(\text{or} A_3)$ and A_{12}. The throughput of such a configuration can be shown to be

$$\lambda^c(p,\rho) = \sum_{k=1}^{\overline{1-\rho}n} \sum_{k_1=1}^{\rho n} \binom{\overline{1-\rho}n}{k} \binom{\rho n}{k} p^{k+k_1}(1-p)^{n-k-k_1} \left[2kP_{k+k_1}(P_T,0) + k_1 P_{k+k_1}^c(P_T,1)\right],$$

where $P_k(P_T,0)$ is as given in equation 6 and $P_k^c(P_T,1)$ is as given in equation 14. It can be shown that

$$\sum_{k=1}^{\overline{1-\rho}n} \sum_{k_1=1}^{\rho n} \binom{\overline{1-\rho}n}{k} \binom{\rho n}{k} k = \sum_{t=1}^{n} \binom{n}{t} \rho t \text{ where } t = k + k_1.$$

Therefore,

$$\begin{aligned} & \lambda^c(p,\rho) \\ = & \sum_{t=1}^{n} \binom{n}{t} p^t (1-p)^{n-t} \left[2(1-\rho)tP_t(P_T,0) + \rho t P_t^c(P_T,1)\right] \\ = & (1-\rho)2\sum_{t=1}^{n} \binom{n}{t} tP_t(P_T,0) + \rho \sum_{t=1}^{n} \binom{n}{t} tP_t^c(P_T,1) \\ \le & (1-\rho)\max_p \lambda^c(p,0) + \rho \max_p \lambda^c(p,1) \end{aligned}$$

□□□

The above theorem shows that, under the given conditions, the throughput of a system with partial overlap is less than the throughput of either one of the extreme configurations. In other words, the throughput is a convex U function of the fraction of overlap. Although the condition imposed in Theorem 2 is stringent, the intuition is that the result extends to the general case as well. This is clearly illustrated in the figure 6.

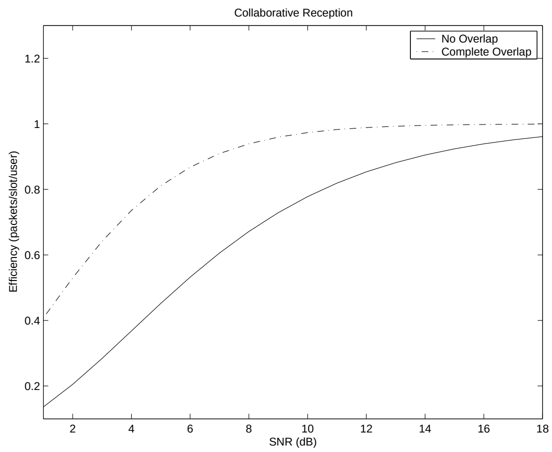

Fig. 7. Efficiency of SENMA with two cooperative Mobile Access Points

Figure 7 shows that even in the co-operative MAP case, the efficiency of the completely overlapped network is uniformly better than other configurations. This is evident from the following theorem

Theorem 3: For any given P_T

i) $\eta^c(\rho) = \max_p \eta^c(p,\rho) = \frac{2(1-\rho)P_1(P_T,0)+\rho P_1^c(P_T,1)}{2-\rho}$

ii) $\max_p \eta^c(p,\rho) \leq \max_p \eta^c(p,1)$

Proof: i) By following the same arguments used in the proof of ii) in theorem 1, it can be shown that the efficiency is given by:

$$\begin{aligned} \eta^c(\rho) &= \lim_{p\to 0} \frac{\lambda^c(p,\rho)}{(2n_1+n_2)p} \\ &= \frac{2n_1 P_1(P_T,0) + n_2 P_1^c(P_T,1)}{2n_1+n_2} \\ &= \frac{2(1-\rho)P_1(P_T,0)+\rho P_1^c(P_T,1)}{2-\rho} \qquad (17) \end{aligned}$$

ii) It remains to be shown that $\eta^c(p,\rho)$ is a monotonically increasing function for $0 < \rho < 1$. The derivative of $\eta^c(\rho)$ with respect to ρ is given by

$$\frac{d}{d\rho}\eta(\rho) = \frac{2P_1^c(P_T) - 2P_1(P_T)}{(2-\rho)^2} \qquad (18)$$

Since $P_1^c(\cdot)$ is the probability of coherent reception by two MAPs in a single user transmission, it is strictly greater than $P_1(\cdot)$, which is the probability of success at a single AP. Therefore, the derivative in the above equation is strictly positive and hence $\eta(\cdot)$ is an increasing function in the given range, and ii) is true.

□□□

V. Conclusion

In this paper, we analyzed the performance of SENMA with two mobile access points in different configurations. An important conclusion from the paper is that partial or imperfect overlap configuration cannot provide the maximum throughput. The analysis in the paper does not explicitly use the distribution of the fading parameter, and hence these results may apply to a general fading model.

References

[1] L. Tong, Q. Zhao, and S. Adireddy, "Sensor Networks with Mobile Agents," in *Proc. 2003 Military Communications Intl Symp.*, Boston, MA, Oct. 2003.

[2] P. Venkitasubramaniam, S. Adireddy, and L.Tong, "Sensor Networks with Mobile Agents: Optimal Random Access and Coding," *to appear in IEEE Journal on Sel. Areas in Comm.: Special Issue on Sensor Networks*, `http://acsp.ece.cornell.edu/pubJ.html`.

[3] G.Mergen, Q. Zhao, and L.Tong, "Sensor networks with mobile access: Energy and capacity considerations," *submitted to IEEE Trans. on Communications*, Mar. 2004.

[4] G. Mergen and L. Tong, "Capacity Considerations for Sensor Networks with Mobile Agents," in *Proceedings of the 41st Allerton Conf. on Communications, Control, and Computing*, Monticello, IL, Oct. 2003.

[5] B.Hajek, A.Krishna, and R.O.LaMaire, "On the Capture Probability for a Large Number of Stations," *IEEE Trans. Communications*, vol. 45, no. 2, pp. 254–260, February 1997.

[6] M.Zorzi and R.Rao, "Capture and retransmission control in mobile radio," *IEEE J. Select. Areas Commun.*, vol. 12, no. 8, pp. 1289–1298, October 1994.

[7] J. Winters, "Optimal Combining in Digital Mobile Radio with Cochannel Interference," *IEEE J. Select Areas in Comm*, vol. 2, no. 4, pp. 528–539, July 1984.

[8] W. Jakes, *Microwave Mobile Communications*. New York: Wiley, 1974.