Interference and Sink Capacity of Wireless CDMA Sensor Networks with Layered Architecture

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We evaluate the sink capacity of wireless code division multiple access (CDMA) sensor networks with layered architecture. We introduce a model of interference at a sink considering two kinds of interference: multiple access interference (MAI) and node interference (NI). We also investigate the activity of sensor nodes around the sink in relation to gathering data under a layered architecture. Based on the interference model and the activity of sensor nodes around the sink, we derive the failure probability of the transmission from a source node located one hop away from the sink using Gaussian approximation. Under the requirement of 1% failure probability of transmission, we determine the sink capacity, which is defined as the maximum number of concurrent sensor nodes located one hop away from the sink. We demonstrate that as the node activity of the MAI decreases, the variation of the sink capacity due to the node activity of the NI becomes more significant. The analysis results are verified through computer simulations.

Keywords: Interference model, node activity, sink capacity, layered architecture, wireless CDMA sensor networks (WCSNs).

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I. Introduction

Recent advances in wireless communications and micro-electromechanical systems (MEMS) technology have enabled the development of wireless sensor networks (WSNs), which are highly distributed networks of tiny, low-cost and lightweight sensor nodes [1]. There are two important operations in WSNs. One is data dissemination, that is, the propagation of data/queries throughout the network, and the other is data gathering, that is, the collection of observed data from the individual sensor nodes to a sink. For data gathering operations, such as battlefield surveillance, real-time monitoring of seismic waves, machine operations, and bush fires, network throughput and packet latency are critical in order to guarantee accurate and timely delivery of sensed data. To deal with this issue, there have been several studies of wireless CDMA sensor networks (WCSNs) [2], [3].

A key concern of wireless networks is the limited capacity of the wireless channel, which is affected by various surroundings. There are many different traffic scenarios, different constraints (such as, bandwidth, average power, and peak power), different network topologies, node placement, and so on. Several studies of various scenarios have been performed focusing on traffic between node-to-node pairs (namely, source-to-destination pairs). In the landmark paper [4], both for arbitrarily located nodes and randomly located nodes, the capacity of each node (in terms of bit-meters per second) was analyzed for wireless networks based on both a noninterference protocol model and the physical model, where a required SINR was specified for successful reception. In [5], Bilatrup and others used a simplified theoretical network model in which the locations of nodes are fixed, to address capacity and performance issues in sensor networks. In [6], Gastpar and others studied the

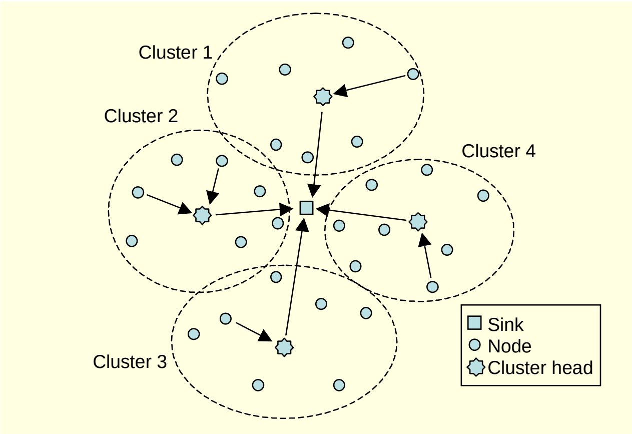

Fig. 1. Clustered architecture.

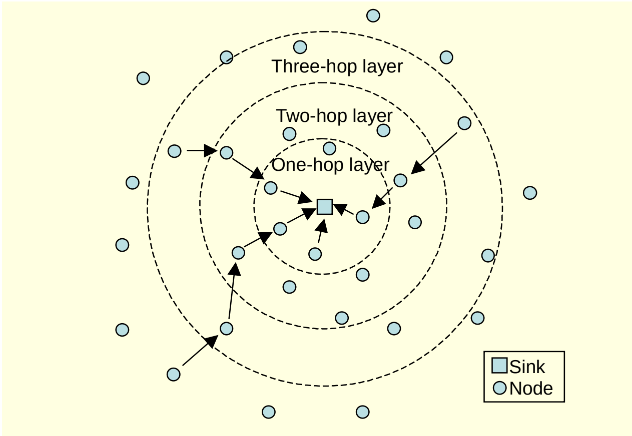

Fig. 2. Layered architecture.

asymptotic capacity of a wireless relay network when there is only one active source-sink pair and all other nodes assist transmission.

Since the capacity issues of sensor networks mainly deal with the traffic carrying capabilities among node-to-node pairs, there has been little attention paid to the sink even though it is the important interface between a manager and a number of sensor nodes. If the manager requests operations that need to be performed by sensor nodes, the sink delivers them to sensor nodes and sends corrected sensor reports, responses, and notifications back to the manager. Based on the method of delivering data from the sensor nodes to the sink, there are two kinds of network architecture: clustered and layered [7].

As shown in Fig. 1, a clustered architecture organizes the sensor nodes into clusters, each governed by a powerful cluster head. The sensor nodes in each cluster directly communicate with their respective cluster heads, whereas the cluster heads directly communicate with the sink. Thus, two-hop transmission is required to deliver the data from the sensor node to the sink. Clustered architecture is especially useful for sensor networks that require data fusion capability. The data gathered by all sensor nodes of each cluster can be fused at each cluster head, and only the resulting data needs to be reported to the sink. However, the cluster head must be more powerful (having a larger battery, higher bandwidth, more memory, more intelligence, and a faster processor) than the sensor nodes.

On the other hand, layered architecture has the sink at the center of concentric layers, and the layers of sensor nodes surrounding it correspond to the sensor nodes that have the same hop-count as the sink shown in Fig. 2. The sensor nodes that are not located in the one-hop layer cannot directly communicate with the sink. Their information should be relayed through the sensor nodes located in the lower hop layers in order to be delivered to the sink. In other words, multi-hop transmission is needed to deliver the data from the sensor node to the sink. Layered architecture is used in multi-hop infrastructure network architecture (MINA) [7]. The advantage of layered architecture is that each sensor node is only involved in short distances. A short transmission range can reduce energy consumption and interference in highly dense sensor networks [8].

II. Related Work and Our Contribution

There have been several studies related to the sink. In [9], Venkitasubramaniam and others proposed random access and coding schemes for sensor networks with a mobile access point, or sink, which is capable of performing required tasks from information retrieval and processing to network maintenance. In [10], multiple sink network design problems are considered. To maximize the lifetime of large scale sensor networks, the networks are divided into smaller sub-networks. With regard to the data gathering operation at the sink, [11] considered a network of N sensor nodes located in the arbitrary plane including one designated sink where the sensed data eventually has to be gathered. The achievable rate of sensor networks is based on the physical model presented in [4]. The results of [11] have implications for the design of efficient data gathering protocols. In this paper, we mainly focus on a model of interference at the sink and the activity of sensor nodes around the sink to evaluate the sink capacity of WCSNs with layered architecture.

An interference model for sensor networks was introduced in [2] and [3]. It considers the interference power to the desired node located at the origin, which is caused by an interference node transmitting its data to its own destination node (not the desired node). Even though the received signal at each sensor node is perfectly power-controlled, the interference power to the desired node cannot be power-controlled. This is because the transmission power from the interference node is controlled by its own destination node. This interference model is useful when we consider sensor networks that use peer-to-peer communication among sensor nodes.

However, a model of interference at the sink should additionally include the interference power which is caused by an interference node transmitting its data to the sink. Note that the transmission power from this interference node can be power-controlled by the sink. With respect to this, we introduce a model of interference at the sink considering two kinds of interference at the sink: multiple access interference (MAI) and node interference (NI). The MAI is generated by the interference power which is caused by an interference node transmitting its data to the sink. The transmission power from this interference node can be power-controlled by the sink. On the other hand, the NI is generated by the interference power which is caused by an interference node transmitting its data to its own destination node (not the sink). The transmission power from this interference node is controlled by its own destination node, not the sink.

The activity of the sensor nodes is an important system parameter for battery-powered sensor networks because, in some cases, sensor nodes might be in sleep mode to conserve power. Consequently, node activity might not always be 1. Especially for the data gathering operation under a layered architecture, the activity of sensor nodes around the sink might be an important factor in evaluating the sink capacity. Sensor nodes near the sink are more active as they relay more data towards the sink.

The remainder of this paper is organized as follows. In section III, we describe the network and interference model. In section IV, based on the interference model and the activity of sensor nodes around the sink, we derive the failure probability of the transmission from the source/relay node located in the one-hop layer to the sink. On that basis, we evaluate the sink capacity of the network. Numerical results and discussion are given in section V. Finally, conclusions are given in section VI.

III. Network and Interference Model

In a WCSN with layered architecture, each node is assigned a unique binary signature code. The network uses CDMA technology [2], [3] and two kinds of spreading code: short code and long code. Short code and long code uniquely identify each layer and each sensor node, respectively. Therefore, the different spreading codes can be uniquely assigned to the different sensor nodes regardless of processing gain. Note that the problem of spreading code assignment is beyond the scope of our paper. We assume the following:

- Sensor nodes and the sink are static.
- Each node and the sink have an omni-directional transmission and reception antenna of the same gain.
- N sensor nodes are randomly, uniformly distributed over a sensor field of area A.
- Each node has a bounded normalized maximum transmission power, P_t [2].
- Between node j and node k, the channel gain is represented by $\gamma_{jk} = d_{jk}^{-\alpha}$, where d_{jk} is the internodal distance and α is a path loss parameter.
- The received signals at each sensor node and the sink are perfectly power-controlled so that each received signal is equal to the lowest possible operational threshold, P_r.
- The sink has a carrier sense threshold (CST), P_i [2]. The CST is well known as the parameter that affects both interference level and spatial reuse [12].
- Throughout the sensor field, we assume homogeneous sources which have the same statistical characteristic even though the locations of sources are different. In other words, all sensor nodes collect data with the same level of activity. With this general assumption, the activity of sensor node j, χ_j, can be modeled as the following binomial distribution:

$$\chi_j = \begin{cases} 1, & \text{with probability } \varepsilon, \\ 0, & \text{with probability } 1 - \varepsilon. \end{cases} \tag{1}$$

For the data gathering operation under a layered architecture, however, sensor nodes near the sink are more active as they relay more data towards the sink because of multi-hop relaying. Therefore, it is natural that sensor nodes near the sink will have larger ε.

We consider two kinds of interference at the sink as shown in Fig. 3. One is interference from the transmitters located within the one-hop layer which directly communicate with the sink (refer to dotted red arrows). The other is interference from the transmitters located within the interference range of the sink (possibly including the one-hop layer and upper layers as shown in Fig. 3) which communicate with other sensor nodes except the sink, as in the interference mentioned in [2], [3] (see dotted blue arrows). In relation to the sink, we differentiate between these two kinds of interference. MAI corresponds to the former and NI corresponds to the latter.

As shown in Fig. 3, let us suppose that the sink, s, is receiving the information from the source/relay node d. Since only the nodes located in the one-hop layer can directly communicate with the sink, the concurrent nodes that are sending their information to the sink within the one-hop layer of area πr_R^2 would bring about the MAI, where r_R is the maximum transmission range of each node. Based on our network model, r_R is given as $\sqrt[\alpha]{P_t/P_r}$. In the figure, node j can be regarded as the MAI.

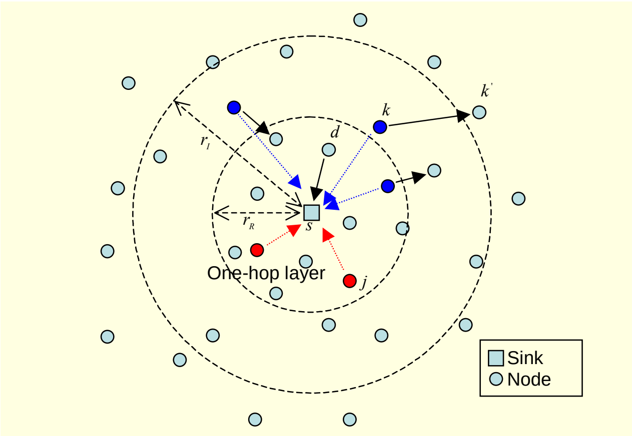

Fig. 3. Interference model at the sink.

On the other hand, let us suppose that the source/relay node k is sending its information to its own destination node k' (Note that it can be any sensor node except the sink). Due to the interference range for the sink, the transmitting signal power generated by the source/relay node k might be sensed at the sink. We call this interference the NI. Based on our network model, the NI might be generated by the source/relay nodes located in the circular area of radius r_I, that is, the area of πr_I^2, where r_I is the interference range of the sink and r_I is given by $\sqrt[\alpha]{P_t/P_I}$. For a source-destination pair, the transmission signal power at the source node k is represented by $P_r \cdot \gamma_{kk'}^{-1}$, where $\gamma_{kk'}$ is the channel gain between the source node k and the destination node k'; therefore, the received interference signal power at the sink due to the node k, which is transmitting its information to its own destination node k', can be calculated as $P_r \cdot \gamma_{kk'}^{-1} \cdot \gamma_{ks}$.

Because N sensor nodes are uniformly random distributed over a sensor field of area A, the probability that the sink has n interferers corresponding to the NI is binomially distributed:

$$P[n \text{ interferers in the NI range}] = \binom{N-1}{n}\left(\frac{a_I}{A}\right)^n\left(1-\frac{a_I}{A}\right)^{N-n-1}, \quad (2)$$

where a_I is the area covered by the interferers corresponding to the NI, that is, $a_I = \pi r_I^2$. For large N and small a_I/A, (2) is well approximated by the Poisson distribution [13]

$$P[n \text{ interferers in the NI range}] \approx \frac{(\rho a_I)^n}{n!} e^{-\rho a_I}, \quad (3)$$

where $\rho = N/A$ is the node density.

Under the existence of the interferers corresponding to both the MAI and the NI, the transmission from the source/relay node d, located within the one-hop layer, at rate R packets/s is successfully received by the sink if

$$\frac{L \cdot P_r}{N_o + \underbrace{\sum_{j=1, j\neq d}^{C_{oh}-1} \chi_j P_r}_{MAI} + \underbrace{\sum_{k=1}^{C_{NI}} \chi_k P_r \gamma_{kk'}^{-1} \gamma_{ks}}_{NI}} \geq \beta, \quad (4)$$

where β is the required signal-to-interference-and-noise ratio (SINR) for successful transmission, N_o is the background noise power, $C_{oh}-1$ is the (deterministic) number of concurrent interferers corresponding to the MAI, C_{NI} is the (random) number of interferers corresponding to the NI, χ_j is the node activity of the MAI (with probability ε_{MAI}), χ_k is the node activity of the NI (with probability ε_{NI}), and $L\,(=W/R)$ is the processing gain of the network (W is the bandwidth of the network).

IV. Sink Capacity Analysis

We define the *sink capacity* as the maximum number of concurrent sensor nodes located in the one-hop layer, C_{oh}, where the failure probability of transmission from the source/relay node located within the one-hop layer to the sink is below 1%. Using (4), we can obtain the failure probability of the transmission from the node i located in the one-hop layer to the sink as

$$P_{fail} = P\left[P_r \sum_{j=1, j\neq d}^{C_{oh}-1} \chi_j + \sum_{k=1}^{C_{NI}} \chi_k P_r \gamma_{kk'}^{-1} \cdot \gamma_{ks} > \frac{L \cdot P_r}{\beta} - N_o\right]. \quad (5)$$

By conditioning random variable χ_j with probability ε_{MAI}, we can rewrite (5) as

$$P_{fail} = \sum_{j=1, j\neq d}^{C_{oh}-1} P\left[Z > B_m \,\middle|\, \sum \chi_j = m\right] P\left[\sum \chi_j = m\right], \quad (6)$$

where $Z = \sum_{k=1}^{C_{NI}} Y_k$, $Y_k = \chi_k V_k$, $V_k = P_r \gamma_{kk'}^{-1} \cdot \gamma_{ks}$, and $B_m = L \cdot P_r / \beta - N_o - m \cdot P_r$.

As previously mentioned, random variable V_k is the received interference signal power at the sink due to the NI without the effect of the node activity. Note that random variable Y_k is the received interference signal power at the sink due to NI considering the node activity, χ_k (with probability ε_{NI}). In the following subsection, we first consider the distribution of random variable V_k.

1. Distribution of NI Power at the Sink Considering the Node Activity

To find out the distribution of random variable V_k in (6), that is, the received interference signal power at the sink due to the node k, which is transmitting its information to its own destination node k', we adopt the method used in [2]. As shown in Fig. 3, the transmission power of the node k is a random variable, which is dependent on the distance between node k and node k'. We define this random variable as $x_{kk'}$, where

$$x_{kk'} = P_r d_{kk'}^{\alpha}, \quad d_{kk'} \in (0, r_R]. \tag{7}$$

If we assume that the sink at the origin and the node k use the same receiving frequency, then the received interference power at the sink, which is caused by the transmission from the node k to its own destination node k', is represented by

$$v_k = \frac{x_{kk'}}{d_{ks}^{\alpha}} = \frac{P_r d_{kk'}^{\alpha}}{d_{ks}^{\alpha}}, \quad d_{kk'} \in (0, r_R], \ d_{ks} \in (0, r_I], \tag{8}$$

where random variable d_{ks} denotes the distance from the node k to the sink. In [2], Liu and others found the probability density function (PDF) of random variable V_k as

$$f_{V_k}(v_k) = \begin{cases} a v_k^{\frac{2}{\alpha}-1}, & 0 \le v_k < c, \\ b v_k^{-\frac{2}{\alpha}-1}, & \mathrm{c} \le v_k < d, \end{cases} \tag{9}$$

where $a = \frac{1}{\alpha}\left(\frac{r_I}{r_R}\right)^2 P_r^{-\frac{2}{\alpha}}$, $b = \frac{1}{\alpha}\left(\frac{r_R}{r_I}\right)^2 P_r^{\frac{2}{\alpha}}$, $c = \frac{P_r r_R^{\alpha}}{r_I^{\alpha}}$, and $d = P_r r_R^{\alpha}$.

Now, let us consider the PDF of random variable Y_k. Because χ_k has binomial distribution, Y_k can be obtained as

$$f_{Y_k}(y_k) = \varepsilon_{NI} f_{V_k}(v_k) + (1-\varepsilon_{NI})\delta(y_k), \tag{10}$$

where $\delta(\cdot)$ is the Dirac delta function [14].

2. Evaluation of the Failure Probability

By using Gaussian approximation for random variable Z, (6) can be rewritten as

$$P_{fail} = \sum_{m=0}^{C_{oh}-1} \binom{C_{oh}-1}{m} \varepsilon_{MAI}^{m} (1-\varepsilon_{MAI})^{C_{oh}-1-m} Q\left(\frac{B_m - E[Z]}{\sigma_Z}\right), \tag{11}$$

where $E[Z]$ is the mean of random variable Z, σ_Z is the standard deviation of random variable Z, and $Q(x)$ is Gaussian Q-function defined as

$$Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt. \tag{12}$$

Because random variable Z is the sum of C_{NI} random variables, where C_{NI} is itself a random variable, $E[Z]$ and σ_Z^2 are determined by

$$\begin{aligned} E[Z] &= E[C_{NI}] \cdot E[Y_k] \\ &= \rho\pi r_I^2 \cdot E[Y_k] \end{aligned} \tag{13}$$

and

$$\begin{aligned} \sigma_Z^2 &= E[C_{NI}] \cdot \sigma_{Y_k}^2 + \sigma_{C_{NI}}^2 \cdot \left(E[Y_k^2]\right)^2 \\ &= \rho\pi r_I^2 \cdot E[Y_k^2], \end{aligned} \tag{14}$$

respectively, where we use the fact that since C_{NI} is a Poisson random variable, $E[C_{NI}] = \sigma_{C_{NI}}^2 = \rho\pi r_I^2$. According to (10), the mean and the second moment of random variable Y_k are obtained by

$$\begin{aligned} E[Y_k] &= \int_{-\infty}^{\infty} y_k f_{Y_k}(y_k) dy_k \\ &= \varepsilon_{NI} \int_{-\infty}^{\infty} y_k f_{V_k}(y_k) dy_k + (1-\varepsilon_{NI}) \int_{-\infty}^{\infty} y_k \delta(y_k) dy_k \\ &= \varepsilon_{NI} E[V_k] \\ &= \varepsilon_{NI} \left(\frac{P_r (r_R/r_I)^{\alpha}}{\alpha+2} + \frac{P_r \left(r_R^{\alpha} r_I^{-2} - r_R^{\alpha} r_I^{-\alpha}\right)}{\alpha-2} \right), \end{aligned} \tag{15}$$

and

$$\begin{aligned} E[Y_k^2] &= \int_{-\infty}^{\infty} y_k^2 f_{Y_k}(y_k) dy_k \\ &= \varepsilon_{NI} \int_{-\infty}^{\infty} y_k^2 f_{V_k}(y_k) dy_k + (1-\varepsilon_{NI}) \int_{-\infty}^{\infty} y_k^2 \delta(y_k) dy_k \\ &= \varepsilon_{NI} E[V_k^2] \\ &= \varepsilon_{NI} \left(\frac{P_r^2 (r_R/r_I)^{2\alpha}}{2\alpha+2} + \frac{P_r^2 \left(r_R^{2\alpha} r_I^{-2} - r_R^{2\alpha} r_I^{-2\alpha}\right)}{2\alpha-2} \right), \end{aligned} \tag{16}$$

respectively.

Equation (11) enables us to calculate the failure probability of transmission according to the number of concurrent sensor nodes located within the one-hop layer under given system parameters, and to evaluate the sink capacity of the network. Gaussian approximation may lead to a crude result at low node density. The central limit theorem (CLT) is used to justify Gaussian approximation. According to the theorem, the number of independent and identically distributed elements (that is, C_{NI}) for a reasonably good Gaussian approximation should be greater than 10 [14]. Otherwise, we should evaluate the sink capacity by using computer simulation only. The computer simulation is carried out using the following procedure:

i) Set the system parameters β, L, N_o, P_r, r_I, r_R, ρ, ε_{MAI}, and ε_{NI}.

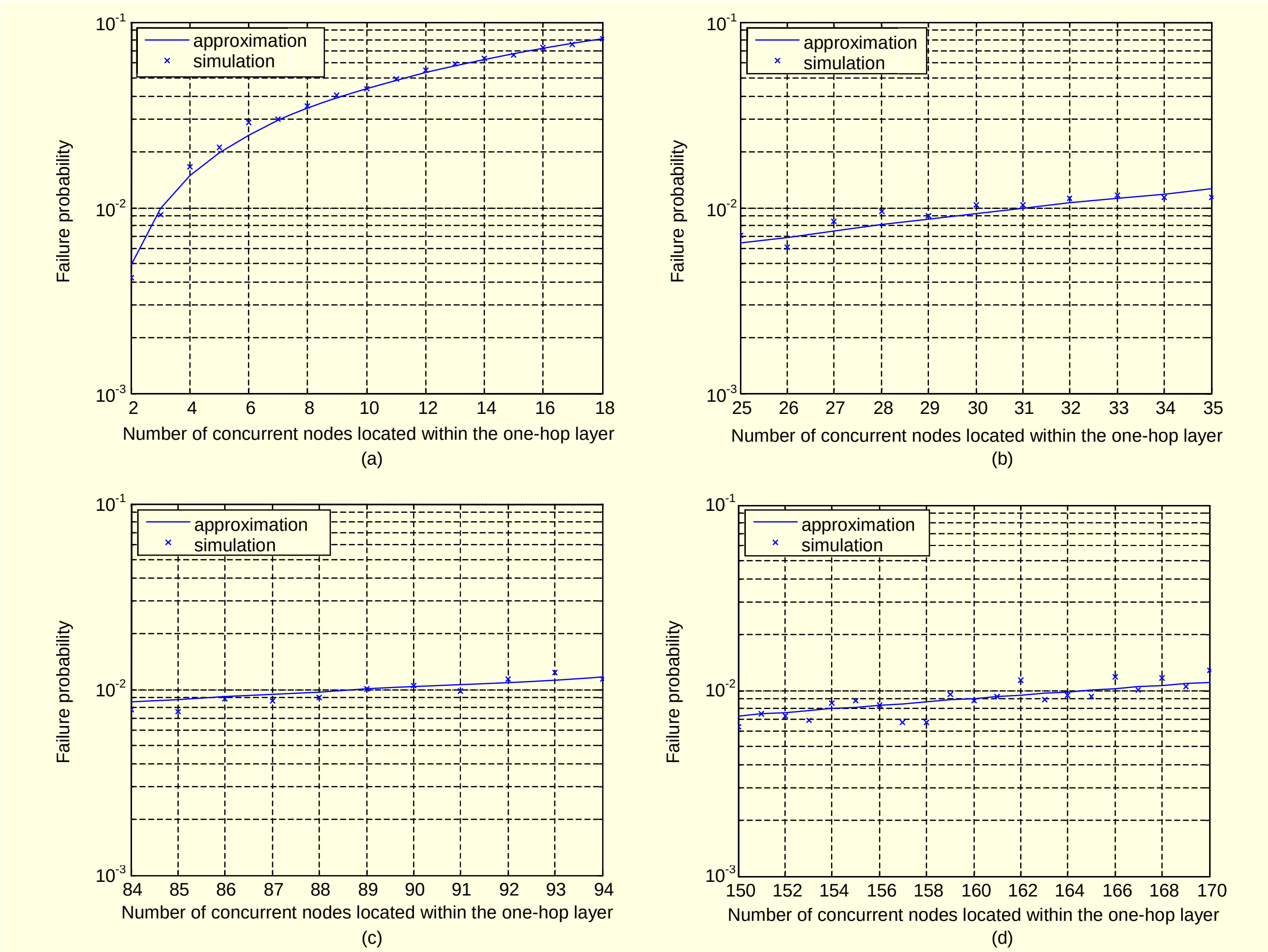

Fig. 4. Failure probability vs. the number of concurrent sensor nodes located within the one-hop layer when ε_{MAI}= 0.005 and ε_{NI}= 0.9 ε_{MAI}: (a) L=4, (b) L=8, (c) L=12, and (d) L=16.

ii) Set the number of interferers corresponding to NI using $E[C_{NI}] = \rho\pi r_I^2$.

iii) Let the number of interferers corresponding to MAI, C_{oh}, be 1.

iv) Generate the random location of NIs over the interference range of the sink, (0, r_I]. Note that, for convenience, the location of the sink is set to the origin (0, 0).

v) Compute the distance between the sink and the k-th NI, d_{ks}, and repeat for all NIs.

vi) Generate the random distance between the k-th NI to its destination node k', $d_{kk'}$, over (0, r_R], and repeat for all NIs.

vii) Compute the received interference signal power at the sink due to the k-th NI, which is transmitting its information to its destination node k', $P_r \cdot \gamma_{kk'}^{-1} \cdot \gamma_{ks}$.

viii) Compute $SINR$ for the node d which is located within the one-hop layer using (4).

ix) Calculate the failure probability for the node d using $P_{fail} = P[SINR < \beta]$.

x) Repeat steps from iv to viii 10,000 times to average the failure probability.

xi) Let C_{oh}=C_{oh}+1 and go back to step iv.

Finally, the sink capacity is determined by the maximum number of C_{oh} that guarantees the failure probability is 1%. In the following section, we evaluate the sink capacity using (11) and verify it through computer simulations.

V. Numerical Results and Discussion

Under the requirement of 1% failure probability of transmission, we investigate the sink capacity according to system parameters, such as the maximum transmission range of each node, the interference range of the sink, the node activity, the node density, the path loss parameter, and the processing gain. We assume that the required SINR is 7 dB, and the required received signal power for the power control (P_r) is -70 dBm (=10^{-10} W), and the background noise power is -110 dBm (=10^{-14} W).

The node density and the interference range of the sink should be carefully set in order to guarantee the validity of Gaussian approximation. From the fact that $r_I \approx 2r_R$ typically [3], r_R and r_I are assumed to be 25 m and 56 m, respectively. Based on r_R and r_I, P_t and P_i are set to $r_R^{\alpha} \cdot P_r$ and $r_I^{\alpha} \cdot P_t$, respectively. The node density, ρ is set to 0.008 where N=2700 and $A = 627.87 \times 537.5\ \text{m}^2$ [3]. The expected number of NIs results in $0.008 \times \pi \times 56^2 \approx 78.82$. Therefore, as mentioned in section IV.2, the validity of Gaussian approximation could be guaranteed.

Figure 4 depicts the failure probability according to the number of concurrent sensor nodes located within the one-hop layer (that is, the sink capacity) when $\varepsilon_{MAI} = 0.005$ and $\varepsilon_{NI} = 0.9\varepsilon_{MAI}$ for different processing gains. The node activity of the NI is assumed to be 90% of the node activity of the MAI since sensor nodes near the sink will have larger ε as mentioned in section III. In addition, the failure probability using Gaussian approximation is compared by using computer simulations. The approximated results match the simulated results well since the expected number of NIs is sufficient for the CLT. Intuitively, we can expect that a higher processing gain will result in a greater sink capacity, since higher processing gain reinforces the SINR value of the desire node. When L is 4, 8, 12, and 16, the resulting sink capacities are 3, 31, 89, and 163, respectively.

Based on (11), Fig. 5 depicts the sink capacity according to the processing gain when $\varepsilon_{MAI} = 0.05$. The node activity of the NI varies considering three different cases: $\varepsilon_{NI} = 0.1\varepsilon_{MAI}$ (for light NI activity), $\varepsilon_{NI} = 0.5\varepsilon_{MAI}$ (for medium NI activity), and $\varepsilon_{NI} = 0.9\varepsilon_{MAI}$ (for heavy NI activity). Compared with Fig. 4, where $\varepsilon_{MAI} = 0.005$ and $\varepsilon_{NI} = 0.9\varepsilon_{MAI}$, the sink capacity greatly depends on the node activity of the MAI. Thus, when L is 4, 8, 12, and 16, the sink capacities result in 0, 4, 9, and 14, respectively. Moreover, the node activity of the NI affects the sink capacity according to the processing gain. We expect that as the processing gain increases, the variation of the sink capacity due to the node activity of the NI becomes more significant.

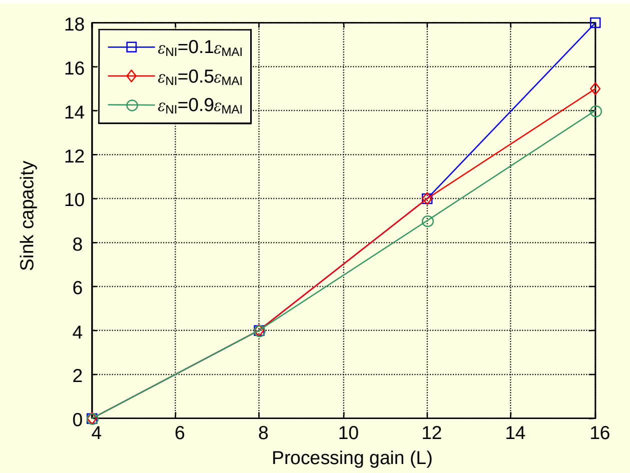

Fig. 5. Sink capacity vs. processing gain when $\varepsilon_{MAI} = 0.05$.

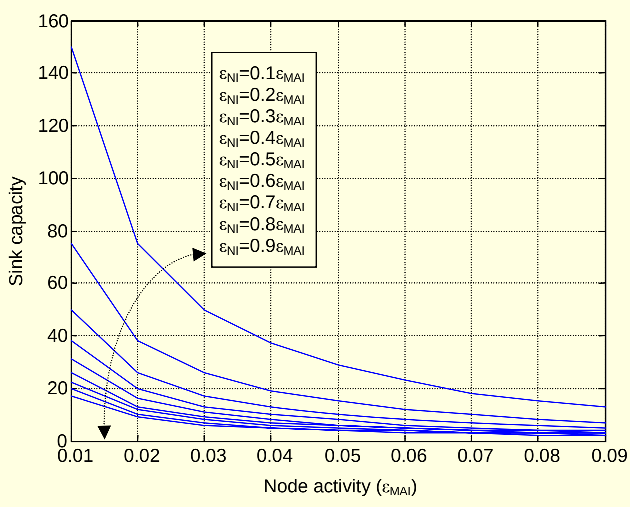

Fig. 6. Sink capacity vs. node activity when L=8.

Based on (11), Fig. 6 depicts the sink capacity according to the node activity of both the MAI and the NI when L=8. The more node activity occurs, the more interference (MAI and NI) grows. Consequently, as the node activity increases the sink capacity decreases. Moreover, as the node activity of the MAI decreases the variation of the sink capacity due to the node activity of the NI becomes more significant. Note that lower node activity guarantees a longer node lifetime as well as greater sink capacity.

VI. Conclusion

In this paper, we evaluated the sink capacity of WCSNs with layered architecture. We introduced a model of interference at the sink considering two kinds of interference: MAI and NI. Regarding the data gathering operation under a layered architecture, we also considered the activity of sensor nodes around the sink because sensor nodes near the sink will be more active as they relay more data towards the sink. Based on the interference model and the activity of sensor nodes around the sink, we derived the failure probability of the transmission from the source/relay node located in the one-hop layer to the sink using Gaussian approximation.

Under the requirement of 1% transmission failure probability, we investigated the sink capacity (that is, the number of concurrent sensor nodes located within the one-hop layer). Numerical results were verified by computer simulations. The variation of the sink capacity according to system parameters, such as node activity and processing gain was also investigated. As the processing gain increases, the variation of the sink capacity due to the node activity of the NI becomes more significant. In addition, as the node activity of the MAI decreases, the variation of the sink capacity due to the node activity of the NI becomes more significant.

Numerical and simulation results demonstrated that system parameters should be carefully designed to obtain a target sink capacity, which is crucial to data gathering operations for specific applications.

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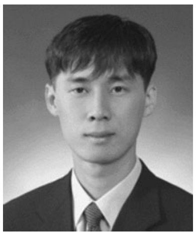

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