Supplemental document for
A Hybrid Memetic Framework for Coverage Optimization in Wireless Sensor Networks

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Abstract— This support document shows the coverage matrix and some additional information regarding the real-world experiment. Moreover, a detailed performance comparison between the proposed method (Hy-MFCO) and other existing approaches is also provided.

Index Terms—Wireless sensor networks, sensor node scheduling, full coverage preservation, network lifetime extension, energy-efficient operation

1 Implementation of the Proposed Hy-MFCO in the Real World

In the proposed method, the coverage matrix $\mathbf{\Phi}_\mathrm{S}$, shown in Supplemental Table 1, is calculated by a coverage evaluation procedure shown in Supplemental Fig. 1. Please refer to the main body of the article for the detailed information with respect to the experimental settings and coverage evaluation procedure.

Supplemental Fig. 2 shows the relative positions of nodes and the disjoint sets that they belong to in the experiment. The nodes that belong to the same set are marked by the same color.

Supplemental Table I

The Coverage Matrix $\mathbf{\Phi}_\mathrm{S}$

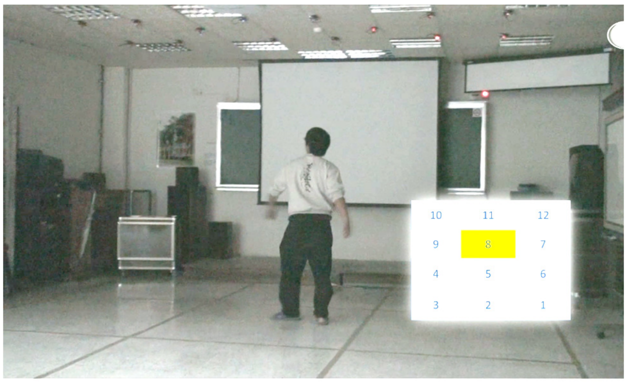
Coverage vector
$\mathbf{\Delta}_{1,\mathrm{S}}$ = [1 0 0 1 0 1 1 1 0 0 0 1 1 1 1 0 0 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0]^T
$\mathbf{\Delta}_{2,\mathrm{S}}$ = [1 1 1 0 0 1 1 1 1 1 0 1 1 1 0 0 0 1 1 1 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0]^T
$\mathbf{\Delta}_{3,\mathrm{S}}$ = [1 1 1 0 0 1 0 1 1 1 0 1 1 1 1 0 0 1 1 1 0 0 1 1 1 0 0 0 0 1 0 0 0 0 0 0 1 0]^T
$\mathbf{\Delta}_{4,\mathrm{S}}$ = [0 0 0 0 0 0 1 1 1 1 0 0 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 0 0 1 1 1 1 0 0 1 1 1]^T
$\mathbf{\Delta}_{5,\mathrm{S}}$ = [1 1 1 1 0 0 0 1 1 1 0 0 1 1 1 1 1 1 1 1 1 0 1 1 1 1 1 1 0 0 1 1 0 0 0 1 1 1 1]^T
$\mathbf{\Delta}_{6,\mathrm{S}}$ = [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 0 0 1 1 1 1 0 0 1 0 1 0 0 0 1 1 1 0]^T
$\mathbf{\Delta}_{7,\mathrm{S}}$ = [1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 0 0 1 1 1 0 0 0 1 0 1 0 0 0 0 0 0 0 0 1 0 1 0]^T
$\mathbf{\Delta}_{8,\mathrm{S}}$ = [1 0 0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 1 0 0 1 1 1 0 0 0 0 1 0 1 0 1 0 1 1]^T
$\mathbf{\Delta}_{9,\mathrm{S}}$ = [0 0 0 1 1 0 0 0 0 0 0 0 1 0 1 1 1 0 0 1 1 1 0 1 1 1 1 1 0 1 1 1 1 0 0 1 1 1]^T
$\mathbf{\Delta}_{10,\mathrm{S}}$ = [0 1 0 0 1 0 0 0 0 0 0 0 1 0 0 1 1 0 0 0 0 1 0 1 0 1 1 0 0 1 0 1 1 1 0 0 0 1]^T
$\mathbf{\Delta}_{11,\mathrm{S}}$ = [0 0 0 0 1 0 0 0 0 1 1 0 0 0 0 1 1 0 0 0 1 1 0 0 0 1 1 1 0 1 0 1 1 0 0 1 0 1]^T
$\mathbf{\Delta}_{12,\mathrm{S}}$ = [0 0 0 1 1 0 0 1 1 1 1 0 0 0 1 1 1 0 0 0 1 1 0 0 0 1 1 0 0 0 0 0 1 0 0 1 0 1]^T

*$\mathbf{\Delta}_{i,\mathrm{S}}$ *denotes the* i^{th} *column vector in* $\mathbf{\Phi}_\mathrm{S}$ *(i.e., the coverage vector of* WMD s_i).

2 Maximize the Network Lifetime while Maintaining Full Coverage

Here, WSNs that all consisted of 400 nodes and 64 POIs were uniformly distributed in a sensing field of 100 m × 100 m. Further, all of the nodes were assumed to be exactly homogeneous (i.e., the same initial energy, 0.25 Joules; the same sensing range (r_s), 17.675 m; and the same size of data packets, 2,000 bits), and they formed a multi-hop CWSN [1] with full sensing coverage. A power-rich sink node was located at the coordinate (50, 200).

In addition, the energy consumption model used in this



Supplemental Figure 1

The practical coverage evaluation procedure

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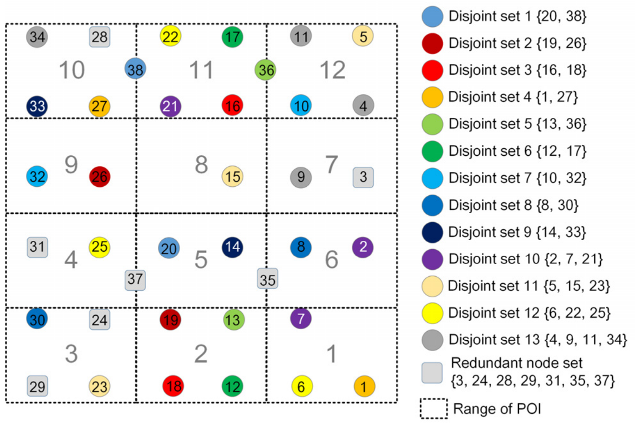


SUPPLEMENTAL FIGURE 2

A map of nodes and their disjoint sets.

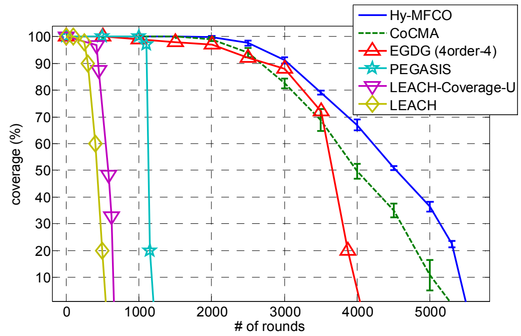
study followed the same model employed in Heinzelman et al. [1]. E_{Tx_NCH} and E_{Tx_CH} denote the energy dissipated for transmitting an H-bit packet for each non-cluster head node and for the cluster head node, respectively. E_{Rx} represents the energy consumption when receiving a packet. They are defined as follows:

$$\begin{aligned} E_{Tx\_NCH}(d,H) &= E_{elec}\times H + E_{amp}\times H\times d^{\beta} \\ E_{Tx\_CH}(d,H) &= (E_{elec}+E_{DA})\times H + E_{amp}\times H\times d^{\beta} \\ E_{Rx}(d,H) &= E_{elec}\times H, \end{aligned} \tag{1}$$

where d is the transmission distance. The parameters used in this model were set as follows: E_{elec} = 50 nJ/bit (dissipated energy on the transmitting circuitry or receiving circuitry per bit); E_{amp} = 100 pJ/bit/m^2 (energy consumption on the power amplifier per bit); E_{DA} = 5 nJ/bit/report (energy for data aggregation); and $\beta = 2$ (path loss exponent).

A variety of approaches have been proposed to accomplish the goals of coverage preservation and network lifetime prolongation, such as CoCMA [2], EGDG (4order-4) [3], PEGASIS [4], LEACH-Coverage-U [5], and LEACH [1]. The performances of these approaches were compared with the performance of Hy-MFCO based on different simulation conditions. It is noteworthy that in CoCMA [2] the nodes are regarded as neighbors if the Euclidean distance between them is smaller than $0.5{\cdot}r_s$, and the possible maximum number of nodes to be awaked is restricted to four, because the computational complexity of the wake-up strategy used in the CoCMA is $O(2^n)$. The experimental results obtained via Hy-MFCO, CoCMA, EDGE (4order-4), PAGASIS, LEACH-Coverage-U, and LEACH are illustrated in Supplemental Fig. 3. The Hy-MFCO prolongs the network lifetime to 5,500 rounds. In addition, the Hy-MFCO is able to maintain 80 percent of the sensing coverage at the 3,500th round. Therefore, the proposed Hy-MFCO is able to effectively improve the network lifetime while retaining the sensing coverage for uniformly deployed WSNs. Randomly deployed WSNs will be considered in the following experiments.

a. Performance Comparison between CoCMA and Hy-MFCO



SUPPLEMENTAL FIGURE 3

Coverage ratio (%) versus rounds for six different approaches in a uniformly deployed scenario.

The CoCMA was known to outperform previously published approaches [2], so we further compared the performances yielded by both CoCMA and Hy-MFCO using different network configurations. We created several simulation cases by varying the number of nodes between 60 and 160 with an increment of 20, the sensing ranges between 100 m and 300 m with an increment of 40 m, and the number of POIs ranging from 10 to 50 with an increment of 10. Other simulation parameters were the same as those used in earlier simulations, except that the size of the sensing field was 500 m × 500 m, that the sink node was located at (250, 250), and that nodes and POIs were randomly deployed. Each simulation case repeated 30 times, and each POI must be covered by at least one node to satisfy the requirement for achieving full sensing coverage. The numbers of rounds under full coverage generated by both Hy-MFCO and CoCMA as well as both the improvement ratio and the p-value of the sign test are summarized in the supplemental Table II.

According to the results, it was found that the Hy-MFCO extends the rounds under full sensing coverage by average 103% compared to the CoCMA. The sign test was performed to determine if the improvement made by the Hy-MFCO was significant. Among all simulation cases, the maximum p-value was 0.00143, which is significant under a 0.05 critical level.

Moreover, it is evident from Supplemental Fig. 4a that the rounds of remaining full coverage increase as the number of nodes increases. This is because both Hy-MFCO and CoCMA are able to optimize the coverage and the lifetime of a WSN by inactivating some redundant nodes to conserve energy of nodes. In Supplemental Fig. 4b, the average rounds under full coverage increase as the sensing range extends, because more POIs can be covered by the node with a wider sensing range. However, Supplemental Fig. 4c shows that the average rounds under full coverage decrease when the number of POIs increases, because it would need more sensor nodes to cover all POIs.

According to the definition, $\acute{\eta}$ is the upper bound for the number of disjoint sets. We can further evaluate whether the number of disjoint sets ($|\check{C}|$) yielded by the Hy-MFCO is close to the theoretical upper bound $\acute{\eta}$ in a given simulation case. In order to perform the evaluation, the effectiveness ($\acute{A}$) (%) of the proposed Hy-MFCO is defined by:

SUPPLEMENTAL TABLE II

EVALUATION RESULTS OF THE PROPOSED HY-MFCO COMPARED WITH THE COCMA [2] REGARDING THE ROUND NUMBER OF ACHIEVING FULL COVERAGE UNDER VARIOUS NUMBERS OF NODES, NUMBERS OF POIS, AND SENSING RANGES

# of nodes	sensing range (m)	# of POIs																			
		10				20				30				40				50			
		μ(H)	μ(C)	r	p	μ(H)	μ(C)	r	p	μ(H)	μ(C)	r	p	μ(H)	μ(C)	r	p	μ(H)	μ(C)	r	p
60	100	72.4	**53.4**	0.68	**3.2E-4**	51.4	**28.7**	1.03	**8.7E-7**	43.4	**23.1**	1.07	**8.4E-6**	40.0	**21.0**	0.99	**1.9E-9**	40.7	**20.4**	1.01	**1.9E-9**
	140	176.4	**87.7**	1.37	**8.4E-6**	132.4	**49.4**	2.15	**1.9E-9**	106.9	**40.7**	2.09	**7.5E-9**	94.9	**42.0**	1.48	**5.8E-8**	91.8	**35.9**	1.97	**5.8E-8**
	180	317.6	**158.3**	1.52	**1.9E-9**	228.5	**104.7**	1.53	**1.9E-9**	204.4	**88.4**	2.32	**1.9E-9**	224.2	**96.3**	1.71	**1.9E-9**	175.8	**65.2**	2.62	**3.7E-9**
	220	604.3	**418.9**	1.02	**1.9E-9**	439.1	**227.4**	1.36	**1.9E-9**	401.6	**265.1**	0.73	**1.9E-9**	399.4	**215.3**	1.30	**1.9E-9**	359.9	**205.9**	0.97	**1.9E-9**
	260	1128.8	**809.2**	0.60	**1.9E-9**	886.3	**676.6**	0.51	**1.9E-9**	908.6	**676.2**	0.49	**1.9E-9**	572.1	**374.9**	0.80	**1.9E-9**	634.5	**422.6**	0.83	**1.9E-9**
	300	2481.7	**2185.5**	0.19	**1.9E-9**	1697.9	**1486.5**	0.19	**1.9E-9**	1294.6	**1097.2**	0.22	**1.9E-9**	1087.8	**807.8**	0.59	**1.9E-9**	1250.7	**1050.8**	0.24	**5.8E-8**
80	100	117.9	**66.3**	0.97	**5.9E-5**	80.3	**44.7**	1.27	**8.4E-6**	74.1	**33.7**	1.58	**8.4E-6**	58.5	**30.1**	1.32	**1.6E-6**	64.5	**27.4**	1.62	**3.7E-9**
	140	239.8	**108.5**	1.42	**5.8E-8**	182.7	**84.8**	1.92	**1.9E-9**	148.3	**66.9**	1.93	**1.9E-9**	132.3	**40.6**	3.35	**5.8E-8**	123.3	**38.0**	2.70	**1.9E-9**
	180	510.0	**238.9**	1.86	**1.9E-9**	373.8	**169.3**	2.10	**1.9E-9**	307.8	**160.6**	1.31	**1.9E-9**	247.9	**115.3**	1.61	**1.9E-9**	233.9	**105.5**	1.89	**1.9E-9**
	220	941.6	**620.3**	1.18	**1.9E-9**	616.1	**414.3**	0.75	**5.8E-8**	532.0	**338.0**	0.80	**1.9E-9**	536.2	**356.8**	0.84	**1.9E-9**	482.1	**328.8**	0.57	**1.9E-9**
	260	1601.9	**1339.2**	0.31	**5.8E-8**	1055.6	**887.6**	0.28	**1.9E-9**	1041.1	**832.0**	0.39	**1.9E-9**	889.5	**707.6**	0.33	**5.8E-8**	849.5	**637.4**	0.43	**1.9E-9**
	300	3000.6	**2706.9**	0.13	**1.9E-9**	2259.3	**2043.0**	0.15	**1.9E-9**	2074.5	**1898.4**	0.11	**1.9E-9**	1733.6	**1570.6**	0.12	**1.9E-9**	1584.1	**1371.7**	0.24	**5.8E-8**
100	100	143.3	**81.4**	0.86	**5.9E-5**	112.3	**55.7**	1.54	**8.4E-6**	94.0	**49.2**	1.42	**1.4E-3**	99.6	**34.9**	2.33	**5.8E-8**	74.3	**30.5**	1.77	**5.8E-8**
	140	321.8	**154.4**	1.53	**5.8E-8**	235.9	**92.2**	2.52	**1.9E-9**	197.6	**66.9**	3.47	**1.9E-9**	189.3	**60.6**	3.35	**1.9E-9**	188.6	**76.6**	2.10	**1.9E-9**
	180	533.8	**306.3**	1.03	**1.9E-9**	420.5	**216.7**	1.46	**1.9E-9**	366.7	**178.5**	2.32	**1.9E-9**	363.6	**206.9**	0.92	**1.9E-9**	340.7	**183.7**	1.09	**3.7E-9**
	220	1243.7	**869.5**	0.54	**1.9E-9**	744.2	**485.5**	0.74	**1.9E-9**	714.4	**529.0**	0.45	**1.9E-9**	704.8	**533.1**	0.41	**1.9E-9**	572.2	**407.2**	0.48	**1.9E-9**
	260	2319.3	**1998.5**	0.32	**1.9E-9**	1422.3	**1197.0**	0.22	**1.9E-9**	1291.6	**1009.4**	0.35	**1.9E-9**	1159.8	**960.3**	0.23	**1.9E-9**	1012.9	**800.4**	0.30	**1.9E-9**
	300	4151.8	**3917.7**	0.07	**1.9E-9**	3177.8	**2776.4**	0.13	**1.9E-9**	2588.9	**2349.2**	0.11	**1.9E-9**	2007.7	**1756.0**	0.15	**1.9E-9**	2003.0	**1798.9**	0.12	**1.9E-9**
120	100	172.0	**103.5**	0.83	**1.5E-5**	155.1	**72.3**	1.44	**5.8E-8**	99.9	**36.4**	2.65	**5.8E-8**	128.6	**44.1**	2.96	**5.9E-5**	119.0	**41.9**	2.25	**1.9E-9**
	140	364.5	**160.3**	1.83	**5.8E-8**	287.7	**119.2**	2.68	**1.9E-9**	236.8	**102.3**	2.51	**1.9E-9**	226.6	**97.0**	1.89	**1.9E-9**	238.4	**86.9**	2.98	**1.9E-9**
	180	696.7	**418.3**	1.12	**5.8E-8**	518.8	**317.9**	0.95	**1.9E-9**	494.5	**291.9**	0.89	**1.9E-9**	454.1	**265.1**	1.28	**1.9E-9**	397.9	**251.9**	0.72	**1.9E-9**
	220	1375.5	**1026.3**	0.77	**1.9E-9**	970.1	**692.5**	0.53	**1.9E-9**	838.0	**644.7**	0.34	**5.8E-8**	843.6	**620.0**	0.38	**1.9E-9**	707.8	**531.6**	0.40	**1.9E-9**
	260	2769.0	**2488.4**	0.15	**5.8E-8**	1835.5	**1651.9**	0.17	**1.9E-9**	1786.8	**1479.8**	0.37	**1.9E-9**	1740.4	**1431.9**	0.24	**1.9E-9**	1388.3	**1191.5**	0.19	**1.9E-9**
	300	5263.9	**4848.6**	0.09	**1.9E-9**	3823.5	**3545.4**	0.09	**1.9E-9**	3039.7	**2797.7**	0.11	**1.9E-9**	2695.1	**2498.7**	0.09	**8.7E-7**	2789.5	**2558.9**	0.11	**5.8E-8**
140	100	206.5	**113.0**	1.14	**3.2E-4**	173.4	**80.0**	1.62	**3.7E-9**	161.3	**56.0**	2.73	**1.9E-9**	140.5	**38.0**	3.38	**1.9E-9**	109.8	**34.8**	2.73	**1.9E-9**
	140	420.4	**215.3**	1.44	**1.9E-9**	297.1	**142.6**	1.86	**1.9E-9**	302.5	**138.3**	2.03	**1.9E-9**	286.5	**110.6**	2.96	**1.9E-9**	238.8	**108.8**	2.47	**1.9E-9**
	180	773.5	**507.5**	0.62	**1.9E-9**	706.3	**451.5**	0.77	**5.8E-8**	553.6	**349.1**	0.83	**1.9E-9**	515.4	**330.2**	0.67	**1.9E-9**	468.4	**303.7**	0.65	**1.9E-9**
	220	1266.3	**956.6**	0.47	**1.9E-9**	1078.0	**846.0**	0.28	**1.9E-9**	1018.7	**796.8**	0.30	**1.9E-9**	848.8	**687.4**	0.25	**1.9E-9**	903.8	**710.4**	0.29	**1.9E-9**
	260	2987.1	**2694.4**	0.11	**1.9E-9**	1981.7	**1710.0**	0.18	**1.9E-9**	1906.0	**1577.9**	0.23	**1.9E-9**	1680.5	**1506.8**	0.12	**1.9E-9**	1593.9	**1369.7**	0.17	**1.9E-9**
	300	4875.1	**4529.1**	0.09	**5.8E-8**	4243.4	**3961.9**	0.11	**5.8E-8**	4263.6	**4004.6**	0.08	**1.9E-9**	3254.9	**2924.5**	0.14	**1.9E-9**	3094.8	**2819.0**	0.11	**1.9E-9**
160	100	289.8	**137.4**	1.41	**5.8E-8**	206.4	**84.3**	1.92	**1.9E-9**	179.1	**67.2**	2.17	**1.1E-7**	150.7	**49.2**	3.12	**1.9E-9**	134.8	**39.0**	3.07	**1.9E-9**
	140	491.8	**268.8**	1.06	**1.9E-9**	392.7	**191.4**	1.29	**5.8E-8**	326.5	**149.5**	2.53	**1.9E-9**	330.5	**138.4**	2.04	**1.9E-9**	323.1	**156.2**	1.35	**1.9E-9**
	180	967.9	**683.6**	0.64	**1.9E-9**	761.4	**497.2**	0.69	**1.9E-9**	599.5	**408.1**	0.62	**1.9E-9**	628.4	**421.2**	0.52	**1.9E-9**	556.2	**382.2**	0.54	**1.9E-9**
	220	1939.2	**1565.6**	0.30	**1.9E-9**	1409.1	**1087.0**	0.34	**1.9E-9**	1160.1	**853.2**	0.43	**1.9E-9**	1162.0	**927.2**	0.32	**1.9E-9**	1095.9	**850.0**	0.31	**1.9E-9**
	260	3255.2	**2824.9**	0.15	**1.9E-9**	2521.8	**2290.8**	0.12	**1.9E-9**	2349.5	**2098.4**	0.13	**1.9E-9**	2179.9	**1897.6**	0.18	**1.9E-9**	1725.4	**1519.9**	0.15	**1.9E-9**
	300	6806.3	**5886.6**	0.13	**1.9E-9**	5095.3	**4667.3**	0.08	**5.8E-8**	4375.1	**4077.4**	0.08	**1.9E-9**	3308.0	**3113.4**	0.08	**1.9E-9**	3924.8	**3674.8**	0.07	**5.8E-8**
Avg. (1)				**78%**				**97%**				**112%**				**118%**				**110%**	
Avg. (2)																				**103%**	

*μ(H) *and* μ(C) *denote the averaged rounds for achieving full coverage; r and p denote the averaged improvement ratio made by Hy-MFCO and p-value of the sign test, respectively; and* Avg. (1) *and* Avg. (2) *denote the averaged improvement ratio for different # of POIs and the average of overall improvement ratios, respectively.*

$$\acute{A} = \frac{|\check{\mathbf{C}}|}{\acute{\eta}}, \tag{2}$$

where $0 \leq \acute{A} \leq 100$ %. The larger value of $\acute{A}$ indicates that the yielded solution is more close to $\acute{\eta}$.

Supplemental Fig. 5 illustrates that the average $\acute{A}$ for each case is larger than 98%. Thus, these simulation results indicate that the proposed Hy-MFCO is able to maximize the number of disjoint sets via the MA-based scheduling strategy and recover the loss of sensing coverage via the HRA.

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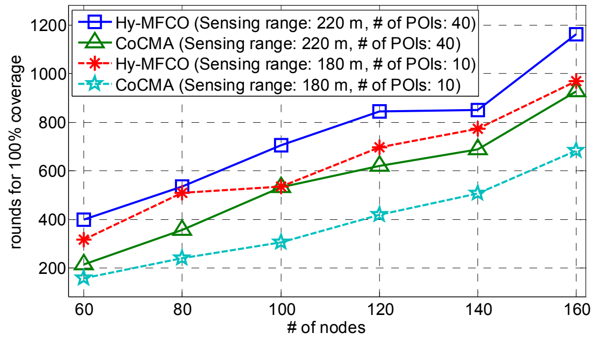
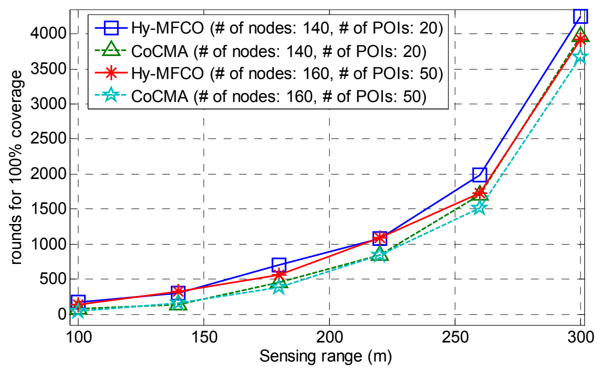


(a)



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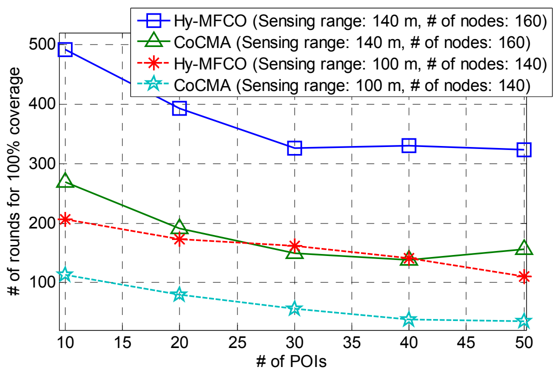
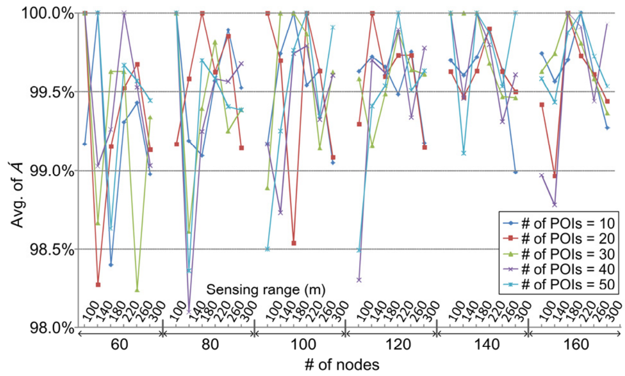


(c)

SUPPLEMENTAL FIG. 4.

Comparison of the average rounds achieved by the proposed Hy-MFCO and the CoCMA [2], (a) in both scenarios: sensing range (m), number of POIs) = (220, 40) and (180, 10), depending on different numbers of nodes (60-160 with an increment of 20); (b) in both scenarios: number of nodes, number of POIs) = (140, 20) and (160, 50), depending on different sensing ranges (100 m-300 m with an increment of 40 m); (c) in both scenarios: (sensing range, number of nodes) = (140, 160) and (100, 140), depending on different numbers of POIs (10-50 with an increment of 10).



SUPPLEMENTAL FIG. 5

Average $\acute{A}$ of every case.