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Increasing the Value of Collected Data and Reducing Energy Consumption using Network Coding and Mobile Sinks in Wireless Sensor Networks

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ABSTRACT: The Wireless Sensor Networks (WSNs) include a number of fixed sensor nodes so that each sink moves to collect data between nodes. It is necessary to determine the optimum route and residence location of mobile sinks to reduce energy consumption and increase the value of collected data, which causes increasing the lifetime of WSNs. Using Network Coding (NC), this paper presents a Mixed Integer Linear Programming Model to determine the multicast Sink Optimal Route (SOR) of Source Sensor Nodes (SSNs) to mobile sinks in WSNs which determines the time and location of sinks to collect maximum coded data and reduce the delay in sinks movement and energy consumption. Since solving this problem is not possible in polynomial time due to the multiple parameters and the limited resources of WSNs, therefore, several heuristic, greedy and fully distributed algorithms are proposed to determine the movement of sinks and their residence location based on maximizing the Value of Collected Coded Data (*VCCD*) and the type of data deadline. It is demonstrated, by simulation, that the optimal model and the use of NC and proposed algorithms, causes reducing the energy consumption and increasing the *VCCD* and network lifetime than non-NC methods.

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1. Introduction

WSNs includes nodes with sensing capabilities and wireless communications that generate data, send them to one or more sinks with several multi-hop and are used to monitor the environment and long-distance communications etc. [1, 2]. The challenges of these networks are related to long term communications and bandwidth constraints [3]. Also, energy, processing and memory resources are unconstrained in sink nodes; however, with the energy discharge in sensor nodes, it is often not possible to charge and relocate them, so that the node dies and is no longer capable of sensation and communication [4]. If the sink is fixed, then sending sensed data from all sensors to the sink will increase the load on the sensor nodes around the sink and their energy will be depleted faster than other nodes and causes the network disconnection. It should also be noted that with increasing sink mobility, the energy consumption for the routing building increases and propagating and network lifetime goes down [5]. Other constraints on these networks include the sink mobility rate, area coverage, minimum sink residence time, and the maximum *VCCD* at places of residence which will reduce over time. Therefore, it is necessary to use energy-aware routing protocols [6].

It is possible to use the data sharing feature using the NC [5, 12]. It has been proved that NC causes maximizing the *VCCD* in multicast routing with one or more SSNs, and thus finding the maximum received *VCCD* is the optimal solution to linear programming problem [33]. Also, NC reduces energy consumption and end-to-end latency [7]. Two routing and coding steps are required to create a connection based on NC. In the routing step, the edges and the value of bandwidth usage are determined, and in the coding step, the operation function of each node is defined in the selected route [8]. The efficiency and function of NC depends on the network topology and how to collect the coded data in the destination nodes [9]. It has been proved in [10] that NC maximizes the multimedia *VCCD* with one or more of SSNs, and if the NC problem is applicable, the problem solution is as linear programming [11]. Most algorithms do not use the NC method to determine the optimal route. The problem of multicast routing based on NC is a linear optimization problem and its optimal solutions are obtained in polynomial time [12].

Fig. 1 shows an example of the use of NC in WSNs that includes 44 sensor nodes, dispersed in a random two-dimensional geographic area, and also 16 residence locations for mobile sinks in a 4×4 grid. The sinks move horizontally or vertically from pinpoint joints to balance energy consumption among nodes. It is supposed that three data of D_1, D_2 and D_3 are generated in this scenario from three ASNs of N_1, N_2 and N_3 respectively, and two mobile sinks S_1 at location x and S_2 at location y collect all of these data. For this purpose, we need five transmissions as follow in normal mode or in store-and-

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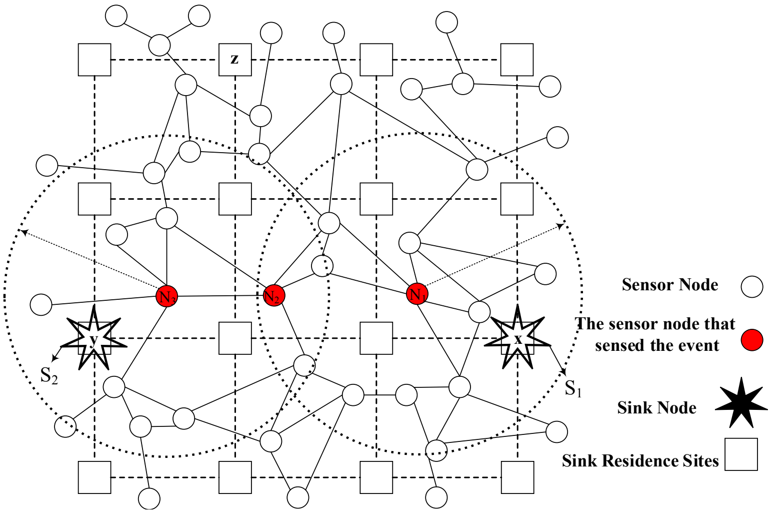

Fig. 1. the use of NC, three wireless SSNs and two mobile sinks

forward without using NC.

- The node N_1 broadcasts the data D_1 and thus, it will be collected at the sink S_1 and the node N_2,
- The node N_2 broadcasts the data D_2 and thus, it will be collected at the S_2 and S_1 sinks,
- The node N_3 broadcasts the data D_3 and thus, it will be collected at the sink S_2 and the node N_2,
- The node N_2 broadcasts the data D_1, and thus, it will be collected at the sinks S_1 and S_2,
- The node N_2 broadcasts the data D_3 and thus, it will be collected at the sinks S_1 and S_2.

However, four transmissions are requires as follows using the NC and store-code-and-forward approach:

- The node N_1 broadcasts the data D_1 and thus, it will be collected at the sink S_1 and the node N_2,
- The node N_3 broadcasts the data D_3, and thus, it will be collected at the sink S_2 and the node N_2,
- The node N_2 broadcasts the data D_2 and thus, it will be collected at the sinks S_2 and S_1.
- The node N_2 XOR data D_1 and D_3 and broadcasts them in the form of one packet and thus, the sinks S_1 and S_2 will collect and decode it, simultaneously.

Therefore, reducing the number of transmissions lead to decrease energy consumption in the nodes. It is noteworthy that the proposed method should determine the sink residential accurate location because, for example, if the sink S_2 is at location z, the NC does not have any effect on reducing the number of transmittals.

The important contributions of this paper includes the following:

- In most of the previous papers, only the mobile sink are used to collect data; however, in the model proposed in this paper, several sink nodes are used to collect coded data.
- In papers [7,13], it is assumed that the time of sinks moving between the start and end points is negligible and the service provider ignores it, however the proposed model considered and measured the value of consumed energy to change the location of the sinks and the time between the start and end points for every sink.
- In most previous papers, the goal is to maximize *VCCD* by sinks; however, in this paper, in addition to this case, the goal is to determine the SOR and reduce energy consumption. It should be noted that increasing sink mobility lead to increase building and propagation of routes and decreases network lifetime.
- The proposed model is independent of the density, deployment of sensor nodes, sink residential locations, the size and shape of the geographic area and the sensor node technical characteristics, such as the sending radius, energy model. The proposed model parameters include the data production and transmission rates, the required energy for data collection and remaining energy of the sensor nodes.
- Most MILP models are focused on determining optimal multicast routing of SSNS to mobile sinks, that needs a lot of time and energy, but in this paper, a new MILP model or Mixed Integer Linear Programming model which in distributed, determines the SOR and residence time and locations all sinks in WSN.
- The proposed algorithms explicitly and greedily control the movement of sinks and determine the sink residence location and time as distributed and based on the nodes remaining energy and the maximum *VCCD*, and if the energy of the nodes and the *VCCD* was more in one location, the sink would move regularly at that location.
- The proposed model can collect data while moving the sink. That is when the sink is in mobility mode, the sensor nodes send their sensed data to the multi-hop by the NC, and thus reduce the latency and the value of stored data in the nodes.

The rest of the paper is structured as follows. Section 2 includes research associated with sink mobility and NC in WSNs and data collection. Section 3 defines an MILP for accurate modeling of the scenario and finding SORs and maximizing *VCCD* with NC. In section 4, several heuristic and distributed algorithms are proposed for sink aware and controlled routing and maximum *VCCD* to determine the time and location of sinks. Section 5 consists of simulating, evaluating and performance comparison of energy consumption, the latency and the VCCD in optimal model and the two unaware methods DataMULE and TSP or the Travelling Salesman Problem without NC, and the same two methods using NC in MATLAB software. Finally, the conclusion and suggestions for future research were provided in section 6.

2. Related Works (Research Background)

The main goal in WSNs is to create balance in load traffic and energy consumption between SSNs and sinks to extend the lifetime of WSNs. Sink mobility protocols are often uncontrollable or random, and controlled or deterministic which can be used based on the application and network conditions, such as data traffic or node remaining energy [14, 15]. There are three general cases for controllable mobility in the WSN [16]. In the first case, the sink itself moves between the sensor nodes and collects the data. In the second case, the moving relays are used to collect data and send them to a fixed sink, and in the third case, the sensor nodes mobility is used. In the first two cases, since sink and relays do not have energy constraint, causes increasing the performance and lifetime of network; however, the mobility of sensor nodes causes increase energy consumption and reduce network lifetime [17, 18]. It is proved in [12] that the use a single sink leads to imbalance of energy consumption, increase delay, and demands more buffer memory, and the use of multi-sinks leads to increased costs and hardware. In [19], it has been proved that the sink mobility around the network border causes increase in energy balance. The reference [20] uses relays or DataMULEs to send and collect data through a hop sensor node to the sink which saves and balances energy consumption and reduces latency. Reference [21] investigated the sensor nodes overflow buffer and minimized the speed of the mobility relay, and demonstrated that since each sensor node knows the current location of the relay node, it improves the routing and network lifetime and reduces the delay to four times compare with the fixed sink. Reference [22] has investigated the problem of constructing and maintaining routes with a mobile sink as unpredictable and uncontrollable. Reference [23] has used sinks with a predictable and fully controllable mobility which the sink is an airplane that flies over the region and collects sensed data periodically. Reference [24] has used an unmanned vehicles to collect data, and sensor nodes send their information to their nearby cluster heads via routing with several multi-ho which reduces the time to send data from an SSN to a cluster head, and the sink only uncontrollably visit the cluster heads.

Reference [25] has investigated sink mobility centralized algorithms among SSNs and them residential location at specific locations and collected data through several multi-hop to reduce energy consumption and maximize the network lifetime. For this purpose, the energy of the remaining nodes is collected centrally at the beginning of each round and identifies the best sink residential locations by solving the MILP model. Improving network lifetime in this way is about five times as long as the sink is in the four corners and the central part of the network. Reference [26] has defined network lifetime maximization, as a minimum-maximum problem which with sink mobility in the network, load balancing and lifetime increases by 500% compared to when the sink is in the center of the network. Reference [27] has used MILP to solve the problem of determining the SOR of mobile multi-sinks. Reference [28] has proposed a general optimization problem to determine the SOR and its residence time at residential locations and proves that this problem is a NP-hard problem and uses heuristic algorithms to solve it and computations. Reference [29] provides a hybrid MILP model based on the maximum distance between two sink successive residential locations in order to determine the SOR and sink residence time in each location, and has proposed a distributed heuristic algorithm to solve it. Reference [30] has provided a genetic algorithm to determine the SOR and reduce delay and proves its effectiveness compared with single sink by simulating and testing.

The COPE architecture is proposed in Reference [31] in which, multi-hop nodes transmit data from SSNS, code and send them to WSNs. The results show that using this architecture in the transport layer without changing the higher layers in the routing will increase performance of network. Reference [9] has used the formulation of topology control and coding in multimedia WSNs to create balance in energy consumption, extend network lifetime and reduce latency. Reference [32] has uses of NC to increase the sent *VCCD* and references [7, 30, 33] has used mathematical formulas to build a multicast routing. It has been shown in [33] that the NC process is performed in binary and logical methods. In the binary coding method, the real data representation of the data bits is used and in the logical coding method, data interference is used in the electromagnetic range in the physical layer which reduces the collision between the data and operational throughput increases. In [34], it has been shown that it is necessary to perform calculations and to combine incoming data in the multi-hop in order to NC. In order to maximize the multimedia *VCCD* with one or more SSNs, the reference [7] has used the NC and sharing, and provides a linear programming model for solving it, so that, the complexity of the problem solving will be linear if the problem is implementable. Reference [35] has used non-linear and non-convex programming based on NC in WSNs in order to reducing energy consumption and control of multicasting topology and [36] has shown, by simulation, that the mobile sink scenarios and the use of linear and random NC causes reducing latency. Reference [37] has used simulation to show that NC reduces the delay in downloading files compared to non-NC applications, and Reference [38] has shown that NC can be used on interactive mobile devices with multiple interfaces.

3. Problem Statement and Presentation an MILP Mathematical Model to Find the SOR

It is supposed in the proposed model that first the sinks move from a hypothetical location, such as 0 or source, and stay in some locations to collect sensed and coded data from SSNs, and broadcast their residence location and time to all sensor nodes. If the sink is in mobile mode, the SSNs send their data to the neighbor multi-hop close to the sink location to be coded and delivered to the sink as multicast. As a result, when moving the sink, no node has stored its sensed data and sends it to several multi-hop to the mobile sinks which reduces the end-to-end latency. The proposed model does not consider the time to process data, the obstacles existence in the WSNs, the energy needed for collection and processing, and assume that the radio coverage is quite regular.

It is also assumed in this paper that *N* is set of SSNs as static and *S* is a set of mobile sinks, and *V* is set of sink residence locations in the form of a 4×4 grid exist in the network and as |*N*|=44, and |*V*|=16 according to in Fig. 1. We use the directed hyper graph *G(N, A)* which is a generalization of the directed graph for modeling of WSNs, in which A is a set of super edges, and each edge can be connected with several SSNs. Each super edge $i{:}J_i$ is consisted of several edges from the of SSN *i* to J_i or a set of neighbors of the SSN i that depends on di or the transmission range the SSN i and the moving sinks in which *i, j*□N, j□J_i. In this section, we first determine the required energy to send a unit of datum, and then present a mathematical model for routing and sending data as multicast and based on NC and consumption energy, that most of constraints are listed references [1-5].

3.1 Determining the NC Model and Reducing Energy Consumption

Since the region is finite in this paper, the proposed algorithms can be implemented in both the free space and multi path models although the free space models are often used. Using the NC, we can use the data sharing feature. It has been proven that NC leads to maximize the collected data in multicast issues with one or more SSNs, and thus finding the maximum *VCCD* is the same as the linear optimal solution programming problem [10]. In order to provide a mathematical model for data routing, and forwarding and collecting as multicast and based on NC, we need to determine the real collected data in each edge that ends up in sinks, so the maximum real *VCCD* must be calculated on each edge [38, 42]. Because the route is changing between SSNs and mobile sinks at each time slice or τ_c, it is necessary to determine the real and virtualized *VCCD* at each time slice which is derived from the virtual *VCCD* to obtain the real *VCCD*. $V^s_{i:j}$ is the virtual *VCCD* from SSN *i* to node j and ends up in sink s□S, and is the real *VCCD* from the SSN *i* to J_i or a set of neighbors of the SSN *i* after coding to ends up in s□S sink which depends on the maximum *VCCD* in each edge. To formulate the above problem, we use mathematical modeling and an MILP model to find SOR in a distributed fashion and minimize the energy consumption which includes the following constraints for sending data in the form of multicast and based on NC [1].

$$V^s_{i:j} \le R^s_{i:J_i} \qquad \forall i, j \in N,\ j \in J_i,\ s \in S \qquad (1)$$

$$0 \le V^s_{i:j} \le C_i \qquad \forall i, j \in N,\ j \in J_i,\ s \in S \qquad (2)$$

$$\sum_{i,j\in N} V^s_{i:j} - \sum_{j\in J_i}\sum_{i,j\in N} V^s_{i:j} = \begin{cases} SD \ if\ i\ is\ source \\ -SD\ if\ i\ is\ sink \\ 0\ otherwise \end{cases} \qquad \forall i, j \in N,\ j \in J_i,\ s \in S \qquad (3)$$

$$E_i = \begin{cases} f(\alpha + \beta_{fs}.{d_i}^2)\ d_i \le d_0 \\ f(\alpha + \beta_{mp}.{d_i}^4)\ d_i \ge d_0 \end{cases} \qquad \forall i \in N,\ d_i > 0 \qquad (4)$$

$$\sum_{\tau_c \in t} E_i.\tau_c.R^s_{i:J_i} \le e0_i \qquad \forall i \in N,\ j \in J_i,\ s \in S \qquad (5)$$

$$minimize: \sum_{\tau_c \in t} \frac{E_i.\tau_c.R^s_{i:J_i}}{e0_i} \qquad \forall i \in N,\ j \in J_i,\ s \in S \qquad (6)$$

$$minimize: \sum_{i\in N}\sum_{\tau_c \in t} \frac{E_i.\tau_c.R^s_{i:J_i}}{e0_i} \qquad \forall i \in N,\ j \in J_i,\ s \in S \qquad (7)$$

Constraint 1 is the main attribute of sharing *VCCD* from the NC in which the virtual *VCCD* is always less than or equal to real VCCD from an SSN, such as *i*□N, to the s□S sink. Constraint 2 specifies the range of the virtual *VCCD* for each edge in the network between the SSN *i* and *j* where C_i is the maximum capacity of SSN *i* [7, 38]. Constraint 3 is the rule for maintaining the multicast *VCCD* based on NC, i.e. for each SSN *i*, the total output *VCCD* minus the sum of the input *VCCD* must be equal to a fixed and non-negative value of supply and demand or SD; then SSNs should be equal to SD and sink nodes equal to -SD, and usual sensor nodes equals zero [22, 29].

Equation (4) expressed how to calculate E_i or the minimum energy required to transmit collected data from the SSN *i* to J_i or the neighboring i. If di or the transmission range node i is greater than constant value d_0, then the multi path energy model is used, and the free space energy model is used, otherwise [29, 39]. Where *f* is the fixed transfer rate in terms of bits per second and if it increasing, then the nodes lifetime increases, and *α* is a non-negative and non-deterministic constant in terms of joule per bit which is dependent on electronic energy, β_{fs} is the amplifier energy consumption in the free space model in terms of *joule/bit/m²*, β_{mp} is the amplifier energy consumption in the multi path model in terms of joule/bit/m4, di is the transmitting range of the SSN *I*, d_0 is a threshold value equal to $\sqrt{(\beta_{fs}/\beta_{mp})}$ [41, 42]. Since the region is limited in this paper, the proposed model and algorithms can be implemented in both free space and multi path models which are often used as free space models.

Constraint 5 calculates the total required energy to send *VCCD* in each SSN *i* to sink s during all time slices τ_c which τ_c is a time slice so that the SSN *i* transfers its data to sink s that is located in a residence location which this value should be less than the $e0_i$ or the initial energy of SSN *i* and *t* is sets all time slots of sink residence in each location [9, 34, 43]. Constraint 6 states that in order to reduce the energy consumption of each SSN such as *i*□N, the total consumed energy dived into the available energy in the same SSN should be minimized

[42-44]. Constraint 7 states that the total consumed energy should be reduced in all nodes in order to reduce the total energy consumption of SSNs and the network. Therefore, this constraint can be an objective function for reducing energy consumption in the optimizing problem of determining the SOR in WSNs based on NC.

3.2 Determining the Continuous Multicast SORs for Mobile Sinks

To provide a mathematical model for routing and sending data as multicast and based on NC, it is necessary to define the following variables and constraints that most of which are listed in Reference [1-5]. First we assume that x and y are the residence locations of sinks and are member of V set, and Ψ_{xy}^{s} is a binary variable that if the sink s□S is going from location x to location y, it is equal to 1, and 0, otherwise and the variable Φ_{x}^{s} is a binary variable that if sink s□S sits at location x, it is equal to 1, and 0, otherwise. If $\Phi_{x}^{s}=1$ then there should be exactly one such location y as $\Psi_{xy}^{s}=1$, and vice versa, if $\Psi_{xy}^{s}=1$, then the sink has to be located at location x, that is, $\Phi_{x}^{s}=1$. Also, if $\Phi_{x}^{s}=0$, then there should be no input from the sink s to location x, also $\Psi_{xy}^{s}=0$ must be true for any location y. The variable $D_{i}^{\tau c}$ is a binary variable, which states that the e_i is equal to 1 if the data from SSN i is sent within the deadline, and 0, otherwise. The variable C_{i}^{t} is a binary variable that is equal to 1 if the data are collected from SSN i at t time, and 0, otherwise.

$$maximize: \sum_{s\in S}\sum_{i\in N}\sum_{t\in[0,T-1]} R_{i:J_i}^{s}.D_{i}^{\tau_c} \quad \forall\, i\in N,, s\in S \;\; \forall\, t\in[0,T-1] \tag{8}$$

Subject to:

$$\Psi_{xy}^{s}\times d_{xy}\le R_{Max} \quad \forall\, x,y\in V, s\in S \tag{9}$$

$$\sum_{x\in V}\Psi_{0x}^{s}=1 \quad \forall\, x\in V, s\in S \tag{10}$$

$$\sum_{x\in V}\Psi_{xq}^{s}=1 \quad \forall\, x\in V, s\in S \tag{11}$$

$$\Psi_{0x}^{s}+\sum_{x\in\Delta_y}\Psi_{xy}^{s}=\Psi_{xq}^{s}+\sum_{y\in\Delta_x}\Psi_{xy}^{s} \quad \forall\, x,y\in V, s\in S \tag{12}$$

$$\Psi_{0x}^{s}+\sum_{x\in\Delta_y}\Psi_{yx}^{s}=\Phi_{x}^{s} \quad \forall\, x,y\in V, s\in S \tag{13}$$

$$\sum_{s\in S}\Phi_{x}^{s}\le 1 \quad \forall\, x\in V, s\in S \tag{14}$$

$$t_{min}.\Phi_{x}^{s}\le t\le M.\Phi_{x}^{s} \quad \forall\, x\in V, s\in S, \;\forall\, t\in[0,T-1] \tag{15}$$

$$C_{x}^{t}\le\Phi_{x}^{s} \quad \forall\, x\in V, s\in S, \;\forall\, t\in[0,T-1] \tag{16}$$

$$\Psi_{xy}^{s}, \Phi_{x}^{s}, D_{i}^{\tau_c}, C_{i}^{t}\in\{0,1\} \quad \forall\, i\in N, s\in S \;\; \forall\, x,y\in V, \;\; \forall\, t\in[0,T-1] \tag{17}$$

Constraint 8 is the second objective function to maximize the real *VCCD* from all SSNs, such as i□N to J_i or a set of neighbors of node i to sink s□S after the NC from time 0 to T-1 or one stage to the end of the network lifetime. Constraint 9 is the maximum distance that a sink s□S can move between the two arbitrary locations x, y□V in the SOR is limited to R_{Max} or the distance maximum between the two sink residential locations. Constraint 10 represents the SOR s□S from the virtual and fixed and arbitrary location 0□V as the source to the arbitrary location x□V. Constraint 11 indicates the SOR s□S of the arbitrary location x□V to the destination or last virtual location q□V at the end of the WSN lifetime. Constraint 12 shows that the number of inputs and outputs to a residential location must be equal where ⍰x is a set of sink residential locations whose distance to residential location x is less than R_{Max}. Constraint 13 shows that the sink s□S can reside at any location x more than once. In other words, the equal left-side counts the number of entries sink s to the residence location x, and the equal right-side is limited to the maximum value of 1 by the binary variable Φ_{x}^{s}. Constraint 14 states that several sinks like s□S can reside in a single time slice in a location such as x□V. Constraint 15 indicates the time interval of stop time or t at a residential location that if the sink s□S is located at x□V, the binary variable Φ_{x}^{s} equals to 1 and t_{min} is the minimum residence time, and M is a large number. With increasing t_{min}, the sink staying time increased in each location, and the overhead of routs building and propagation reduced and energy consumption decreases and the network lifetime increases. Constraint 16 states that the sink s□S should remain until time t in location x□V to collect the coded data. Constraint 17 indicates that Ψ_{xy}^{s},Φ_{x}^{s},$D_{i}^{\tau c}$ and C_{i}^{t} variables are binary. Finally, the proposed optimization model for reducing energy consumption and increasing *VCCD* is as follows.

$$maximize: \sum_{s\in S}\sum_{i\in N}\sum_{t\in[0,T-1]} R_{i:J_i}^{s}.D_{i}^{\tau_c} \quad \forall\, i\in N,, s\in S \;\; \forall\, t\in[0,T-1] \tag{8}$$

$$minimize: \sum_{i\in N}\sum_{\tau_c\in t}\frac{E_i.\tau_c.R_{i:J_i}^{s}}{e0_i} \quad \forall i\in N, j\in J_i, s\in S \tag{7}$$

$$V_{i:j}^{s}\le R_{i:J_i}^{s} \quad \forall i,j\in N, j\in J_i, s\in S \tag{1}$$

$$0\le V_{i:j}^{s}\le C_i \quad \forall i,j\in N, j\in J_i, s\in S \tag{2}$$

$$\sum_{i,j\in N}V_{i:j}^{s}-\sum_{j\in J_i}\sum_{i,j\in N}V_{i:j}^{s} = \begin{cases} SD \text{ if } i \text{ is source} \\ -SD \text{ if } i \text{ is sink} \\ 0 \text{ otherwise}\end{cases} \quad \forall i,j\in N, j\in J_i, s\in S \tag{3}$$

Subject to:

$$\Psi_{xy}^{s}\times d_{xy}\le R_{Max} \quad \forall\, x,y\in V, s\in S \tag{9}$$

$$\sum_{x\in V}\Psi_{0x}^{s}=1 \quad \forall\, x\in V, s\in S \tag{10}$$

$$\sum_{x\in V}\Psi_{xq}^{s}=1 \quad \forall\, x\in V, s\in S \tag{11}$$

$$\Psi_{0x}^{s}+\sum_{x\in\Delta_y}\Psi_{xy}^{s}=\Psi_{xq}^{s}+\sum_{y\in\Delta_x}\Psi_{xy}^{s} \quad \forall\, x,y\in V, s\in S \tag{12}$$

$$\Psi_{0x}^{s}+\sum_{x\in\Delta_y}\Psi_{yx}^{s}=\Phi_{x}^{s} \quad \forall\, x,y\in V, s\in S \tag{13}$$

$$\sum_{s\in S}\Phi_{x}^{s}\le 1 \quad \forall\, x\in V, s\in S \tag{14}$$

$$t_{min}.\Phi_x^s \leq t \leq M.\Phi_x^s \qquad \forall\, x \in V, s \in S, \; \forall\, t \in [0, T-1] \tag{15}$$

$$C_x^t \leq \Phi_x^s \qquad \forall\, x \in V, s \in S, \; \forall\, t \in [0, T-1] \tag{16}$$

$$\Psi_{xy}^s, \Phi_x^s, D_i^{\tau_c}, C_i^t \in \{0,1\} \qquad \forall\, i \in N, s \in S \; \forall\, x, y \in V, \; \forall\, t \in [0, T-1] \tag{17}$$

This model has additional constraints, compared to traditional models, such as the constraint of collecting the coded data in the network. Since there are discrete and stable variables in this model, the model is a Mixed Integer Linear Problem (MILP). There are many algorithms to solve this optimization problem; however, the time and computational complexity of most MILP problems are of the NP-hard type and cannot be solved in a polynomial time [34]. In order to solve these problems and determine SORs based on NC and decrease consumption energy in the WSNs, several heuristic, greedy and distributed algorithms are proposed in the next section which have a good linear computational complexity. Finally, in simulation section, we compare and evaluate the proposed model in terms of energy consumption, data collection and network lifetime with algorithms that use SOR and lack NC.

4. Providing Several Aware and Controlled Heuristic, Greedy and Distributed Algorithms to Determine the SOR

The problem with the MILP optimization model, proposed in the previous section, is the NP-hard nature, minimizing the energy consumption and maximizing the *VCCD* in network. For this purpose, several heuristic, greedy and distributed algorithms are proposed to determine the SOR and the sinks residential time and location is based on minimizing energy consumption and maximizing *VCCD*. In these algorithms, each sink has decided to move to one of the adjacent locations or to stay the residential location after a time t_{min}. This decision is dependent on the remaining energy and the *VCCD* of the SSNs around the new location and the current location of the sinks. Each sink broadcasts its current and new position in a transient range, and each node knows about the sink current position, sends a response packet to the sink with the remaining energy and *VCCD* and the deadline itself. Each sink has decided, based on the response packets, to move to neighborhood residential locations or stay there. Also, for increase the *VCCD* in the proposed algorithms, the sink can be moved or crossed several times in one place. For this purpose, the location where the sink is to be residents or crosses several times is called a logical location with no edges between logical locations, and any logical location is connected to adjacent physical locations. Fig. 2, shows two adjacent physical locations and six logical locations with their connections, allowing for a three-time visit at any physical location. Therefore, the number of visits can be increased in proposed algorithms so that the *VCCD* is maximized.

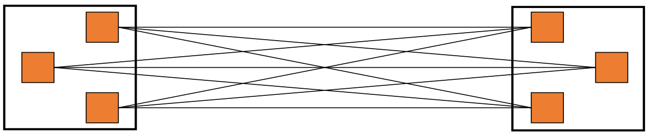

Fig. 2. Two adjacent physical locations, six logical locations and connection between them

If a sink, from a location x□V, collects coded data with a deadline, we use the proposed DFN algorithm to determine the method of collecting the maximum *VCCD* since the network start time up to *T* or the end time of the network operation. The input of this algorithm includes the *x* or residential location sink *s*, t_s or the needed time to store the coded data, *VCCD* or the value of collected coded data, t or the time to predict, t_c or the time to generate a coded data. The output of this algorithm includes $R_{x:Jx}^s$ (t) or the real *VCCD* from the residential location *x* at time *t* and t_{fx} or the time to send the coded data to the sink s□S and M_x or the coded data collection and send method. The time required to generate a coded data depends on the soft or hard deadline and the sink distance to the next residential location. For example, if the *VCCD* of the two locations is the same, visit score is more for the residential location which the nearby data have a hard deadline.

Algorithm DFN (*x*, *t*$_s$, *VCCD*, *t*, *t*$_c$)

```
1    $L_d$ =VCCD based on queue of data info;
2    $R_{x:Jx}^s(t) = 0$;
3    $t_{fx} = 0$;
4    for φ=1 to $|L_d|$ do {
5    $VCCD_φ$ =∑VCCD Transferred φ at a time;
6    $t_φ$ = time it takes to Collect and Transfer all data;
7    if        $VCCD \geq R_{x:Jx}^s(t)$ then $t_{fx}=t_c+t_φ$;
8    if        $t_{fx}>T$     then     break;
9    $R_{x:Jx}^s(t) = VCCD_φ$;
10   $M_x$ = Transfer φ data at a time;        }
11   return ($R_{x:Jx}^s(t)$ , $t_{fx}$, $M_x$);
```

The list L_d is created on line 1, based on coded data from the residential locations, whose length is $|L_d|=[t/t_s]$. In lines 4 through 12, 'for' loop as heuristically and repeatedly calculates and compares the most *VCCD* from the residence location *x*□*V* with multiple methods at any time. The investigation of new methods continues until the coded data Ld can be fragmented at a time and the tfx or final delivery time is less than T or the end of the network operation. The computational complexity of this algorithm is linear and equals to the length of the coded data list for all sensed events or is O($|L_d|$). Using the calculated values of $R_{x:Jx}^s$ (t) and t_{fx} from the above algorithm, we can calculate the score of *VCCD* or *SD* in the residence location *x*□*V* with use formula (18) [1].

$$SD_x = \frac{R_{x:Jx}^S(t)}{t_{fx} - t_{now}} \tag{18}$$

If a sink collects the coded data from both residence locations $x, y \square V$, we use the CSD algorithm to determine the first location close to them. The input of this algorithm is the both residence locations identifier $x, y \square V$ and their prediction time of events equals t and t', and the output is the first sink location based on SD or the *VCCD* score. Lines 3 and 4, compute the *VCCD* from both locations using the DFN algorithm so that the *VCCD* score, obtained from the visit of the residential location $x \square V$, is determined in line 5 before the residential location $y \square V$. Again, the score of *VCCD* obtained from the visit of the residential location y before the residence location $x \square V$ is determined in lines 6 to 9. In line 10, both scores of *VCCD* are compared to determine the first residence location in terms of the highest score. The computational complexity of this algorithm is similar to the DFN algorithm, linear and polynomial and equals to the length of the coded data list for all sensed events or $O(|L_d|)$.

Algorithm CSD (*x, t, y, t'*)

```
1    $t_s$ = recording time of a data;
2    $t_{now}$ = current time;
3    $(R_{x:Jx}^{s}(t), t_{fy}, M_y)$ = DFN $(y, t_s, VCCD, t', t_{fx})$;
4    $(R_{x:Jx}^{s}, t_{fx}, M_i)$ = DFN $(x, t_s, VCCD, t, t_{now})$;
5    $SD_{xy} = (R_{x:Jx}^{s}(t), +R_{x:Jx}^{s}(t'))/(t_{fx}-t_{now})$;
6    $t_{now}$ =current time;
7    $(R_{x:Jx}^{s}, t_{fx}, M_x)$ = DFN $(x, t_s, VCCD, t, t_{fy})$;
8    $(R_{x:Jx}^{s}, t_{fy}, M_y)$ = DFN $(y, t_s, VCCD, t', t_{now})$;
9    $SD_{yx} = (R_{x:Jx}^{s}(t), +R_{x:Jx}^{s}(t'))/(t_{fx}-t_{now})$;
10   if $SD_{xy} > SD_{yx}$ then return $(x, SD_{xy}, M_x)$;
11   else return $(y, SD_{yx}, M_y)$;
```

For example, if the sink collects three coded data from three locations $x, y, z \square V$, then first the sink calculates the score of *VCCD* from each of the three locations using formula (18). If the residence location $x \square V$ has the highest score, the algorithm CSD is executed once with the input (x, y) and again with the input (x, z). If the output of the two runs be $(x, 15, M_x)$ and $(z, 18, M_z)$, respectively, first the sink moves to the location z from the route M_z and collects the coded data, and again the sink decides to move to locations $x, y \square V$.

The algorithm NS is used to determine the next location of sink at the end of each visit and to collect coded data. The input of this algorithm is all *VCCD* in the network and its output is z or the next location of the sink. In lines 1 and 2, first it is needed to select V or a set of sink residence locations containing *VCCD* and calculate the highest *VCCD* from each location $x \square V$. In line 4, the score of *VCCD*, all pairs of possible locations x and y are calculated using the algorithm CSD. In the line 6, the next residence location z determines the highest score for the first visit. The computational complexity of this algorithm equals to $O(|V| \, L_d^{max}|)$ where L_d^{max} is the longest list of coded data records among all sink stay locations in V.

Algorithm NS (*VCCD*)

```
1    $V$ = Set of Sink Residential locations;
2    $x$ = location in V with the highest ;
3    $(z, SD_z)=(0, 0)$;
4    for $y \square V$, $y \neq x$ do  $(xy, SD_{xy})$=CSD$(x, t, y, t')$;
5        if $SD_{xy} > SD_z$ then $(z, SD_z)=(xy, SD_{xy})$
6            return $z$;
```

5. Performance Evaluation and Comparing the Proposed Model and Algorithm with Several Other Methods

This section includes the introduction of simulation scenarios and presentation of results, comparison, and evaluation of proposed optimization model and algorithms with other methods. In these experiments, the sensor nodes are located in a 3×3 square grid Km^2, as shown in Fig. 1, and each sensor node has maximum four neighbors. There are sink locations where the sinks are placed in them randomly in the center of each of the four sensors. It is assumed that any mobile sink can stay and move between locations and two or more sinks reside in one location. Also, it is assumed that the events occurrence location is random and uniform in the simulation model of the network, and the starting point of the sink movement is close to the center of the network, and also it is assumed that the channel is ideal and the transmission between the SSNs is controlled in a coordinated manner from the Media Access Control layer or MAC and no collisions or data error is occurred. SSNs periodically produce multicast coded data based on the Poisson process every 30 minutes with the speed of 10 bits per second.

Simulations in MATLAB environment have been run on a computer with Intel core i5-3210M 2.5 GHz CPU and 6GB memory, and we use CPLEX software and the Pulp Library to solve the proposed MILP model in section 3. The measured values result from an average of 20 runs and simulation iteration, or repeating simulation until that the energy of the first sensor node ends; therefore, the results are with 95% assurance and 5% accuracy. If the value of τ_c time is too long, the network lifetime will end up before the mobile sinks can visit all the locations; therefore causes an unbalance of energy consumption in the SSNs. However, if the value of τ_c time is too short, the mobile sinks will cross all the residence locations before the network lifetime ends, and it will cause in unbalance of energy consumption in the SSNs as well. Therefore, according to some experiments, let τ_c be 40000 seconds, and the runtime of all simulations is 400,000 seconds in order to have the best performance. We consider the value of other simulation parameters as resources [7, 19, 32, 38, 43] as follows.

$R_{Max}=100m$, $e0_i=7j$, $C_i=10kbps$, $\alpha=100pJ/sec.m$, $\beta_{fs}=1nJ/sec$

To evaluate performance, we compare the performance of the NCOPT model, DataMULE, NCDataMULE, TSP, and NCTSP methods. The NCOPT model is the same proposed optimization model in the section 3 of this paper that uses NC, and since it is obtained through an MILP model, it has the best performance and its main parameters are properly adjusted and the obtained route has the most *VCCD*. DataMULE and TSP methods are unaware and random heuristic methods for sink routing and are used in most papers to compare with the proposed methods [44]. The DataMULE method, the multi-hop and the data mules are used for routing and data collection, respectively that since the residence time is

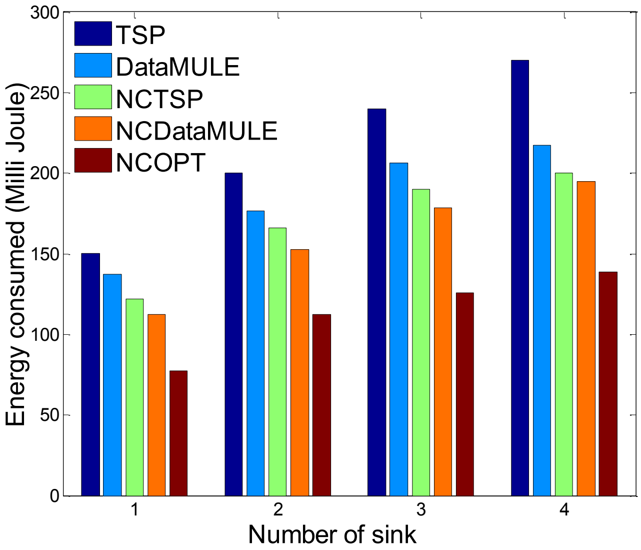

Fig. 3. Fig. 3. The effect of the number of sinks on the average energy consumption by Joule with two SSNs and the transmission range of 10 meters

variable for each sink in this method in each location, we consider the residence time of each sink in each location as constant for a fair comparison. In the TSP method or Travelling Salesman Problem, the sink for collecting coded data before moving, randomly and uniformly specifies the route between the SSNs based on the R_{Max} distance according to Fig. 1,. The problem with the TSP method is that if the node does not sense any event continuing the path, the entire routing will be lost [45]. NCDataMULE and NCTSP methods are the same as DataMULE and TSP methods, except that we use the NC and algorithms in section 4 to determine the SOR and *VCCD*.

Figs 3 and 4 show the results of evaluation and investigation of effect of the number of sink nodes on the total consumed energy in all sensor nodes with two SSNs, with both transmitting range of 10 and 20 meters respectively, in NCOPT model and DataMULE, NCDataMULE, TSP and NCTSP methods. The number of neighbors of each node with a transmitting range of 10 meters, between 2 and 4 and with a transmitting range of 20 meters is between 5 and 12. It is observed that with increase in the number of sinks, energy consumption increases for transmission data to sinks; however, NC opportunity will increase and as a result, causes reducing energy consumption in NCOPT model, and NCDataMULE and NCTSP methods than DataMULE and TSP methods. Since sinks move to locations where NC is done in the NCOPT model, the least energy is consumed, and in this way, the network lifetime will be most, optimal and ideal. It is also observed that the number of neighbors and energy consumption are increased with increasing the transmitting range SSNs; however, with the increasing the number of neighbors, the NC capability is increased and therefore reduces energy consumption in NCOPT model, NCDataMULE and NCTSP methods than DataMULE and NCTSP methods.

Figs 5 and 6 show the results of the evaluating and investigating the effect of the number of SSNs on the total consumed energy in all sensor nodes with 5 sink nodes and for the transmitting range of 10 and 20 m, respectively, in NCOPT model and DataMULE, NCDataMULE, TSP and NCTSP methods. To generate and send data, the number of SSNs can be one of 7 states of 4, 5, 9, 12, 18, 25, and 35 which in 4 SSNs state, four SSNs are located at the four corners of the network and generate the data and other middle nodes code the data. The 5 SSNs state is as the 4 SSNs state and the fifth node is located in the center of the network. In both of these cases, the density of the SSNs is lower, and thus, less data is generated and we need more sinks mobility.

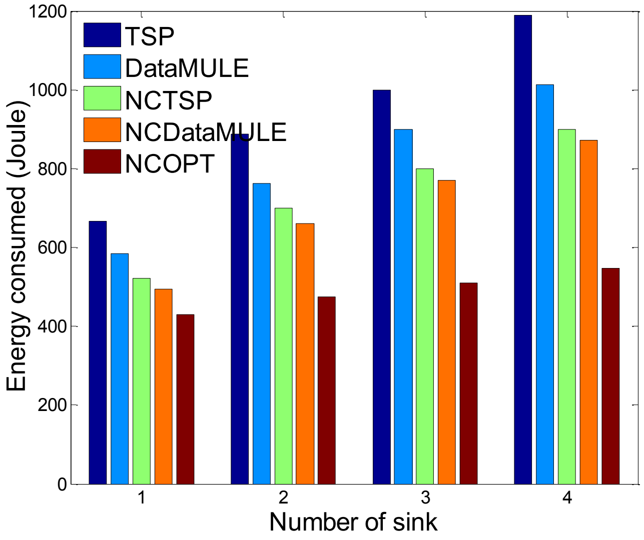

Fig. 4. The effect of the number of sinks on the average energy consumption by Joule with two SSNs and the transmission range of 20 meters

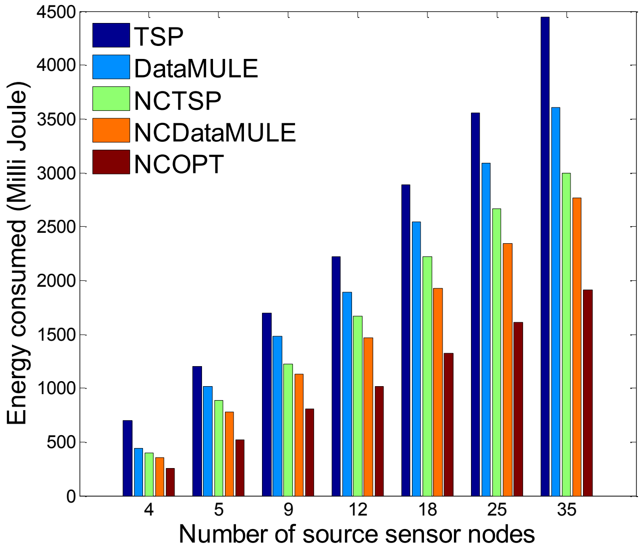

Fig. 5. The effect of the number of SSNs on the average energy consumption by Joule with 5 sinks and the transmission range of 10 meters

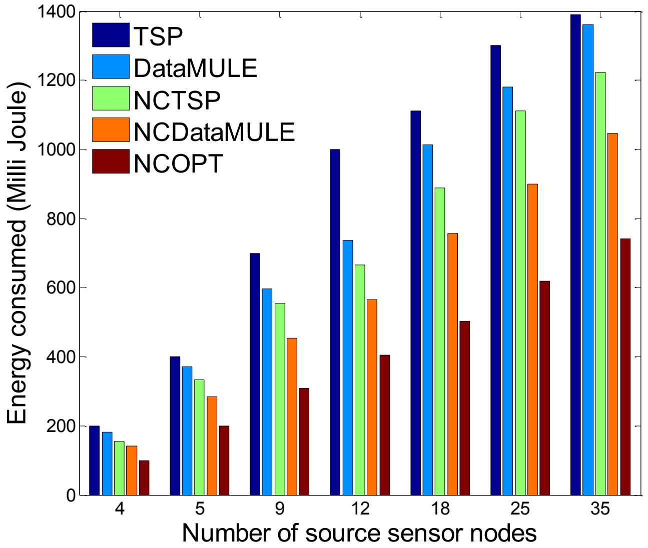

Fig. 6. The effect of the number of SSNs on the average energy consumption by Joule with 5 sinks and the transmission range of 20 meters

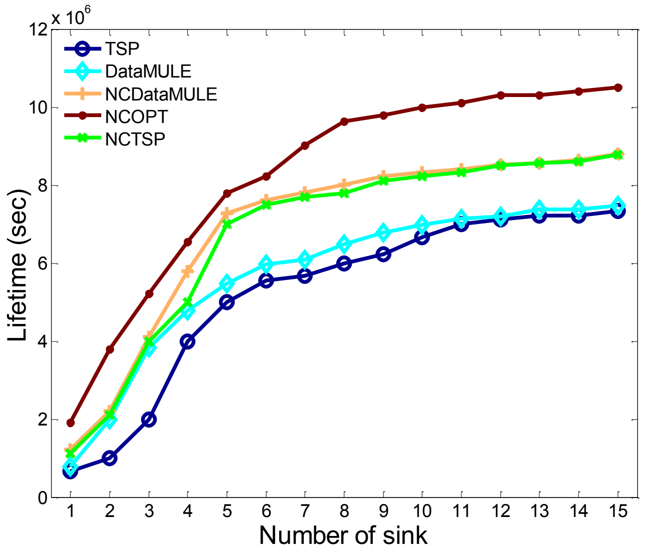

Fig. 7. The effect of the number of sinks on the average network lifetime in second with 3 SSNs and the transmission range of 21 meters

However, in modes where the density of the SSNs grows uniformly over the network, the value of generated data increases and NC can be further utilized, and thus, sinks can much faster collect coded data. It has been observed that by increasing the number of SSNs for data generation and transmission, the traffic load and sent data are increased, and therefore, increased energy consumption and reduced network lifetime. However, using NC lead to decrease of the number of sending and therefore, decrease data traffic and the number of failures and acceptance errors, and thus, decrease energy consumption and increase network lifetime. It has also been observed that with increasing the number of SSNs, the difference between coded and no other coding methods is determined. NCDataMULE and NCTSP methods also have a common view of NC and use NC only to find sink residence locations and therefore, have a weaker performance than the NCOPT model.

Fig. 7 shows the results of the evaluation and investigation of effect of the number of sinks on the network lifetime with 3 SSNs and the transmitting range of 10 meters with NCOPT model and DataMULE and NCDataMULE, TSP and NCTSP methods. In this paper, following the references [9, 31], the network lifetime is defined as the time from the deployment of sensor nodes to energy depletion of the first sensor node. It has been observed that because the NCOPT model and NCDataMULE, NCTSP methods use NC and determine the SOR and suitable locations for residential sinks, causes reducing the time needed to reach sinks to appropriate locations and thus, decrease energy consumption and increase network lifetime time. Also, with the increase the number of sinks, sinks mobility have reduced and to collect multicast data, less sink mobility is required, thus reduced the energy consumption and longer network lifetime. However, we know that the highest energy consumption in WSNs is related to the mobility of sinks and collecting the coded data in the sink, so increasing the number of sinks will increase energy consumption and reduce network lifetime. Therefore, we should specify the optimal number of sinks to balance energy consumption and network lifetime. Finding the exact number of optimal sinks depends on the network parameters, and currently, there is no way to find its exact number. However, it has been observed that the NCOPT model has the longest the network lifetime than other methods. By increasing the number of sinks from 1 to 8, the network lifetime has grown steadily and with more than 8 sinks, the network lifetime will not change, and eventually, with excessive increase number of sinks, the network lifetime is reduced.

Fig. 8 shows the results of the evaluation and investigation

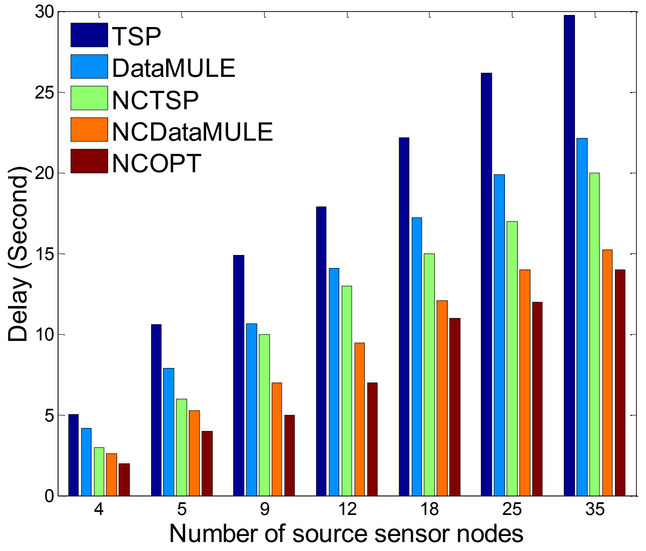

Fig. 8. The effect of the number of SSNs on the average network latency in minutes with 4 sinks and the transmission range of 20 meters

of effect of the number of SSNs on the end-to-end delay with 4 sinks and the transmission range of 20 meter with NCOPT model and DataMULE and NCDataMULE, TSP and NCTSP methods. The end-to-end latency depends on the size of the buffer, the traffic load, and the number of multi-hop between the SSN and the sinks. In this test, the buffer size of the SSNs is 100 kilobytes, and the generated *VCCD* at random intervals with exponential distribution is 100 bytes, and the number of simulations is 100 times; then, we calculate the average of all end-to-end delays. It has been observed that with the increase in the number of SSNs, the *VCCD* is increased at the network level and the needed time to reach the coded data in the sink and delay increases. Also, it has been observed that since NCOPT model and NCDataMULE and NCTSP methods use NC, lead to decrease of the interference and collision of data in the physical layer and therefore, have less delay than the DataMULE and TSP methods.

In a hard deadline case, decreasing the *VCCD* over time is much more than the soft deadline case, so in the hard deadline case, the coded data must be collected rapidly. The *VCCD* from each SSNs to single hop or sink have reverse ratio to the distance between them and with increasing the distance between the nodes, the *VCCD* is reduced.

Figs 9 and 10, shows the results of the evaluation and analysis of the effect of the number of SSNs on the *VCCD* until the 20th minute for the soft and hard deadlines respectively with NCOPT model and DataMULE, NCDataMULE, TSP and NCTSP methods which is independent of network size and coded data storage time. It has been observed that since the NCOPT model is centralized and optimized, and it uses sink aware movement to achieve occurring events on the network, reduce the movement distance and increase the *VCCD*. Also, by increasing the density of the SSNs, the *VCCD* rate increases in all methods and in both the soft and hard deadlines. In this case, the NCDataMULE and NCTSP methods collect only 20 percent the coded data less than the NCOPT model. In the NCTSP method, the sink has to stop in a series of locations to collect coded data which lead to end of the data deadline and the *VCCD* decreases. Because we assumed that the sinks would start from the center of the network, if the number of SSNs is 4, then sinks moved more distances from the four corners of the grid which may end the deadline for some data. However, with the increase in the number of SSNs, such as 35 nodes, the deployment of the SSNs in the center are increased, and is reduced the distance between the SSNs to the sinks, and sinks can collect much more coded data before the deadline, and so with increasing the number SSNs, difference *VCCD* are reduced between NCOPT model and NCDataMULE and NCTSP methods and are increased between DataMULE and TSP methods. Also, because the NCDataMULE and NCTSP methods use NC and algorithms in section 4 of this paper to collect data, movement and selection of the routing of sinks is only on the basis of the data collection score. Therefore, moving routing of sinks is aware and every sink knows in advance that it must go to locations to collect coded data that has a hard deadline and then move to locations where their data still have enough deadline or soft deadline. As a result, sinks in the NCDataMULE and NCTSP methods visited more locations than non-coded methods, and collect more coded data (about the *VCCD* in the NCOPT model). Also, it has been observed that by increasing the number of SSNS in the network, the difference in the VCCD between the methods is increased.

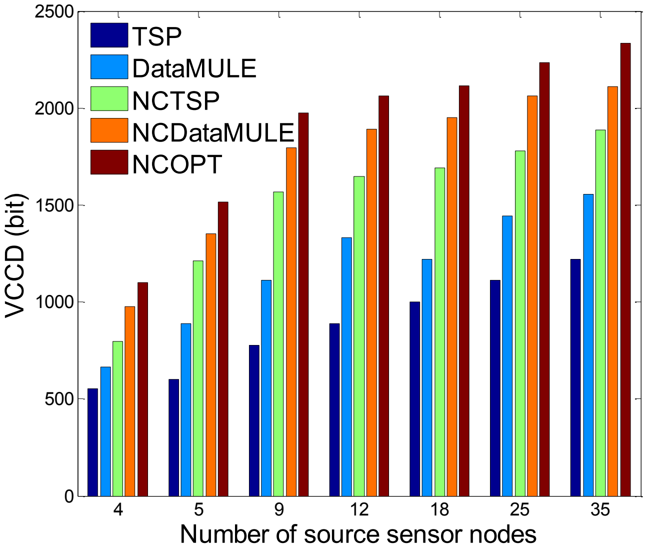

Fig. 9. The effect of the number of SSNs on the VCCD in bits with soft deadline

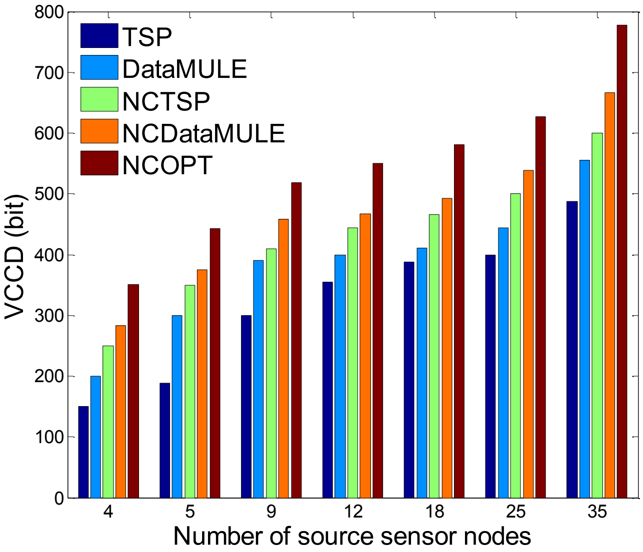

Fig. 10. The effect of the number of SSNs on the *VCCD* in bits with hard deadline

6. Conclusion

Using mobile sinks and NC techniques causes reducing energy consumption and increasing the *VCCD* in WSNs network. In this paper, the problem of determining the SOR and finding optimal residential locations for mobile sinks has been proposed as a MILP along with NC. The problem of finding the SOR and the maximum *VCCD* with more than two SSNs is an NP-hard problem which a convex model, and the greedy heuristic algorithms is proposed to solve this optimization problem. The effectiveness of the proposed optimization model and proposed heuristic algorithms with multiple simulation exercises, based on the number of sink nodes and the number of SSNs, has been investigated and the results show that routing on base multicast coding can improve the average network lifetime, energy consumption, *VCCD* and delays, because of sink informed control and movement. It also shows that increasing the number of sinks to a suitable number increases the network lifetime, but more than that, energy consumption is increased and network lifetime is reduced. Future research in this regard can be focused on choosing optimal values to determine the optimal residential time sinks, using a distributed method for collecting information, determining the SOR based on NC and the use of a non-ideal communication channel in WSNs.

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