Performance Analysis of Coded Mobile WSNs Applied for Radiometry Based on Direct Diffusion Routing

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Abstract – The wireless sensor networks WSNs can be implemented in order to provide a good monitoring solution or an area. A lot of physical quantities can be monitored and processed. The radiometry field is so important that it should be permanently monitored. The sensors, in a WSN, may be empowered through an energy harvesting tool that can increase their lifetime. This manuscript is concerned with the study of sensors, which are energy harvested, that can monitor radiometry field in an environment. In this manuscript, the authors try to increase the downlink harvesting power for the sensors. Moreover, they try to increase the uplink spectral efficiency SE of the sensor. Furthermore, a power control algorithm is applied in order to optimize the anchor nodes transmission power "downlink power". Through the existing proposal, there is a goal to increase the sensor downlink power through coherent energy harvesting models. In addition, there is a trial to reduce and optimize the energy consumption through applying modern routing and coding schemes. The applied coding technique, which is the trellis coded modulation TCM, can improve the signal to noise ratio SNR that results in more SE improvement.

Keywords: Radiometry, Nuclear Radiation, Measurement, WSN, Energy Harvesting, and Uplink Capacity.

I. Introduction

The WSNs can be used for monitoring purposes as well as control over an environment or an industrial process. The randomly distributed sensors can collect the measurement data about an environment. Then, this data may be processed in the sensors themselves before having more processing at a central processor. The transmission of data and information, in a WSN, can be carried out through multi-hop links. This type of communication should be carried out over high reliable links as they are useful information that can share in decision making. Therefore, channel coding is very vital in these networks. In order to save the transmission power, the sensors may select one of them to be the cluster head. This head is able to collect the measured data from the sensors and send them to a remote center. This clustering can be carried out through a lot of routing protocol, in such a way that, one cluster head can route the measured and control data of the sensors that exist in the cluster. The WSN may be qualified to take pictures and videos in addition to the original measured quantity. This category of WSNs can be called multimedia one. This type requires more reliable and high capacities communication links. Although, there are a lot of challenges in multimedia, this type of WSNs is the unique one that can provide the best ubiquitous monitoring process [1-7].

In order to empower the wireless sensors, the solar cells may be used. In fact, this biasing type can increase the sensor lifetime. However, this solution is not suitable for night operation. Moreover, some sensors may be employed to collect data in dark regions wherein there is no solar energy. The best solution for these sensors is the wireless power transfer WPT or energy harvesting. This solution can assure permanent power supply for the sensors as the surrounding environment is overcrowded with a lot of competing radio systems. Really, the energy harvesting can be considered as a suitable tool toward energizing the WSNs with a constant energy anywhere over the day. The free space is overcrowded with radio systems as there are a lot of radiation that comes from; mobile systems, radar systems, wireless systems, and much more. The collected radiation from different wireless systems can be collected by sensors. This radiation can be converted to a direct voltage after rectifications and filtering. The resulting direct voltage can charge the sensor batteries in order to let them operate for longer and longer time. Really, the energy harvesting can be applied for cellular systems to add with the existing batteries especially for short range communication only [8-13].

Radiometry is the word that refers to the radiation measurement process. The free space is overcrowded with a lot of wireless systems. Moreover, when the radiation level exceeds certain values, it may have a bad impact on the human health. Therefore, there should be a powerful tool for radiation measurement. Really, the authors of [14] concluded a lot of radiation measurement tools. However, they did not consider the WSN for measurements. In fact, the WSNs can be implemented everywhere. Moreover, they have a low cost. Furthermore, they can provide a wide coverage.

In this paper, a WSN is proposed in order to provide radiation measurement in an environment. The proposed WSN is energy harvested. Moreover, the anchor nodes themselves will energize the existing sensors with the suitable power during the downlink transmission. The existing anchor nodes can transmit the same data symbols in a synchronous manner to the sensors in order to increase the collected energy at these sensors. The synchronized symbols can provide powerful signals at each sensor. Furthermore, the uplink SE for sensors is given in a closed formula. In addition, the direct diffusion routing is applied in order to save the sensors' consumed energy especially during their transmission. This means that the proposed WSN is a power efficient one. Moreover, in order to have reliable communication links between the sensors and the anchors, the TCM codes are applied. In brief, the authors try to design a WSN able to best fit in radiometry measurement purposes and this WSN is a power efficient one that can provide reliable communication services

II. Related Work

The mobile cellular systems can provide a wide coverage for a public land mobile network "PLMN". The PLMN is divided into clusters in which each cluster has seven cells. Each one is covered by a base station. This base station can provide electromagnetic radiation, through its coverage area, in order to provide a ubiquitous coverage for its serving users. The existing base stations, in a cellular system, should provide a uniform field distribution over the coverage area. In order to keep a uniform field distribution, a simple monitoring tool was implemented in [15] wherein the authors tried to implement a cheap and a low-cost monitoring tool based on embedded WSN. By the same way, the authors of [16] developed a monitoring system that can collect radiation dose stably. Moreover, the measured values are digitized and then they are sent to a remote computer for more processing.

In [17], the authors tried to mathematically formulate the electromagnetic field before implementation of a suitable monitoring tool from their point of view. The given mathematical solution can let them find the optimal solutions. They already applied the genetic algorithms to find the best solution of their large deployment problem. On the other side, [18] tried to improve the radiation properties of the WSN itself. They tried to select the best location for a sensor that can optimize the radiation. They put the sensors in a circular form in order to ease the analysis process and in order to improve the beam forming gain. In brief, they proposed intelligent circular sensor node array. They already obtained better gain than the previous work.

[19] tried to implement a WSN that was able to measure the radiation levels especially at nuclear facilities. They tried to implement a low cost WSN equipped with a radiation sensor. They already used low cost chips depend on Arduino kits. Their system could monitor, control, and record the instantaneous radiation levels. Furthermore, it supported a warning system that can give alarm when the radiation levels exceed certain threshold. They also tried to keep the performance of the communication links, inside the WSN, in order to confirm a reliable WSN. By the same way, [20] discussed the implementation of a Zigbee WSN able to monitor the nuclear radiation levels. The authors tried to reduce the energy consumption of the designed system. The most interesting thing in their design is the application of a sleep mode which can reduce the energy consumption.

In [21], the implantation of a WSN that was able to measure the nuclear radiation, especially in power plants, was handled. The authors used sensors that can withstand high temperature and radiation values. Moreover, the used sensors were compatible to the surrounding environment. They confirmed that by applying electromagnetic compatibility EMC test of the system after implementation. The authors concentrated on the implementation of EMC sensors in their system. The nuclear radiation monitoring is also handled in [22] wherein the authors tried to implement a monitoring system that can provide alarm especially when the nuclear radiation levels exceed certain levels. Moreover, they tried to implement a centralized monitoring WSN in order to record the events. [23] designed a radiation monitoring tool depending on the WSNs that were able to monitor the harm levels if they are reached. This system can avoid the existence of danger in the radiation fields. The fore-mentioned system can monitor nuclear radiation well. In [24], the nuclear radiation is also measured. The implemented system can send the measured quantities over a distance of 10 km. The fore-mentioned system can allow a lot of different sensors that could measure and send their measured data to a base station. The system also could be implemented in urban areas.

The energy harvesting is a powerful tool toward energizing the limited battery devices with suitable energy levels. The WSNs can be based on energy harvesting theory. Moreover, it can fit well in cellular system where device to device D2D communication or very short-range communication dominates. [25] handled a detailed survey on mobile recharging techniques for rechargeable WSNs. On the other side, [26] studied the use of a reinforced concrete battery for powering WSNs. Moreover, they tried to apply energy harvesting technique in order to empower the sensors which are widely spread. [27] proposed a reconfigurable DC–DC converter for maximum thermoelectric generator TEG energy harvesting in a battery-powered duty-cycling wireless sensor node. They applied discontinuous energy harvesting, which operates in single-input dual-output SIDO boost, battery-TEG pile-up buck BTPB, dual-phase buck–boost DPBB, and battery supplied buck modes with a single shared inductor. [28] dealt with the energy harvested WSNs in order to improve the performance. The authors tried to save the battery-limited devices through application of novel routing protocols. [29] explained the synchronization among the sensors, in a WSN, by applying low energy level symbols. In [30], the energy harvesting was applied in order to solve a binary distributed detection problem in a WSN. Although the wireless channels were faded, the sensors can harvest energy that qualified them to communicate efficiently. Moreover, they can also communicate with a fusion center whose function is the processing for all received data. In [31], orthogonal frequency-division multiplexing OFDM based downlink simultaneous wireless information and power transfer SWIPT is considered in the Internet of Things IoT wireless interference network, wherein one hybrid access point HAP performs both wireless power transfer WPT and wireless information transfer WIT to energy harvesting EH and information decoding ID nodes while multiple coexisting energy access points EAPs carry energy to EH nodes.

[32] handled the energy harvesting in an IoT based sensors network. The authors investigated how to dynamically allocate the limited harvested energy for sensing and transmission to maximize the overall network utility in EH-IoT. A perturbation-based Lyapunov technique is applied to tradeoff the optimality gap and system stabilization and an online distributed algorithm is proposed to pursue the close-to-optimal network utility in EH-IoT. [33] investigated a secure transmission in an energy harvesting EH sensor network in the presence of non-colluding passive eavesdroppers, where the EH sensors communicate with a controller via a buffer-aided relay “sink node”. Each sensor has a battery to accumulate the energy harvested from the radio frequency RF signals transmitted by the relay, and purely relies on the harvested energy to perform transmission. In [34], a status updating system was considered in which data from multiple sources were sampled by an energy harvesting sensor and transmitted to a remote destination through an erasure channel. The goal was to deliver status updates of all sources in a timely manner, such that the cumulative long term average age of information AoI is minimized.

[35] tried to implement a novel RF energy harvesting technique along with an intelligent dynamic energy flow control algorithm. The algorithm works with dedicated energy flow control hardware. The implemented system was also able to provide perpetual life time to the ultra-low power sensor nodes. A close approximation of the size of the RF energy harvester array was proposed for the perpetual lifetime of the WSN node deployed with wake-up radio for event-based monitoring applications. They verified their work through application of mathematical models, simulation, and a manufactured prototype. [36] tried to implement an energy harvested WSN able to cover a wide area. Moreover, they tried to minimize the energy usage through discovering novel data collection techniques. By the same way, [37] handled an IoT status update system with users, energy harvesting sensors, and a cache-enabled edge node. On the other side, [38] introduced a receiver design for an energy harvesting sensor node SN. The receiver is equipped with multiple radio frequency RF inputs. Furthermore, the receiver contains separate circuitries for information decoding ID and energy harvesting EH with dynamic power splitting PS. The ID and EH circuits are connected to a power splitter that first combines all the RF inputs and then splits the power between the circuitries.

This manuscript is focusing on the design of a WSN that can be applied in radiometry field. The proposed WSN can provide reliable communication among the sensors as well as anchors due to the application of the TCM codes. Moreover, the proposed WSN is a very power efficient one due to the energy harvested sensors as well as the application of direct diffusion routing algorithm. Moreover, the power control algorithms can reduce the transmission power of a sensor during the communication process for optimization issues without affecting the downlink harvesting energy. The main contribution of this manuscript can be stated as follow;

- The energy harvesting is applied for energizing the sensors. Moreover, a lot of anchor nodes are allowed to transmit their symbols in a synchronous manner. Moreover, the transmitted energy of the anchors is optimized in order to increase the energy efficiency of the whole system.
- There are novel mathematical formulas for the downlink harvested energy as well as the uplink SE.
- The proposed WSN is simulated in order to estimate the energy harvesting performance and the SE performance of the network uplink.
- The energy efficiency of the sensors is optimized through application of power control and direct diffusion routing.
- The reliability and the SE are optimized through application of the TCM codes.

Our paper is organized as follows; Section 3 provides the mathematical analysis of proposed WSN. Subsequently, the TCM codes are explained in Section 4. After that, the direct diffusion routing is demonstrated in Section 5. Then, the simulation results are displayed and analyzed in Section 6. Finally, conclusions, about the paper, are given.

III. Mathematical Analysis

We consider a WSN wherein there are; sensor nodes as well as anchor ones. Let symbol L refers to the number of existing anchors and k is the number of single antenna sensors. In addition, each anchor node is equipped with N antennas. The existing number of antennas is connected to the core network through reliable fronthaul links. The time division duplex is assumed in order to provide the reciprocity between the uplink and downlink. The total transmission frame can be mathematically given by;

$$\tau_p+\tau_d+\tau_u=\tau_c \tag{1}$$

where τ_p refers to the pilot length, τ_d refers to the downlink transmission time, τ_u refers to the uplink transmission time, and τ_c refers to the total coherence frame time. Keep in your mind that the pilots are used for channel estimation. The channel realization parameter g_{kl} can be achieved according to the following equation;

$$g_{kl} = e^{j\theta_{kl}}\overline{g}_{kl} + \tilde{g}_{kl}, \tag{2}$$

where the first term refers to the NLOS component whereas the second term refers to the LOS path loss component that include; both LOS and shadowing, and much more. The pilots are used for channel estimation. Assume that there are mutually orthogonal pilot signals which are; $\varphi_1, \varphi_2, \varphi_3, \ldots, \varphi_{\tau p}$. Each of them has a length τ_p. These pilots can be applied for control processes. The number of orthogonal pilots may be less than the number of served users. In other words, a lot of users can operate on the same pilot signal which results in a pilot contamination. When the UEs transmit their pilots, the received pilot signal can be expressed as;

$$Z_l = \sum_{k=1}^{K} \sqrt{\rho_p}\, g_{kl}\varphi_k^{\mathrm{T}} + N_l, \tag{3}$$

where ρ_p refers to the transmission power and its square root refers to the voltage level. $(\ldots)^T$ refers to the vector transpose. Nl is the noise in the communication path. Φ_T is the transmitted signal transpose whereas gkl gives an indication of the channel parameter. The pilot signal is correlated, at the receiver, with a repeated replica in order to extract the channel parameters. The correlation signal, Z_{kl} can be mathematically expressed as follow;

$$Z_{kl} = \frac{Z_l\varphi_k^*}{\sqrt{\tau_p}} = \sqrt{\tau_p\rho_p}\ \sum_{i\in P_k} g_{il} + n_{kl}, \tag{4}$$

The channel parameter, g_{kl} , can be given by;

$$\hat{g}_{kl} = \sqrt{\tau_p\rho_p}\mathbf{R}_{kl}\boldsymbol{\psi}_{\mathrm{kl}}^{-1}\mathbf{z}_{kl}, \tag{5}$$

The channel estimate can be given through the autocorrelation estimation vector, R_{kl} , as follows;

$$\mathbf{R}_{kl} \triangleq \mathbb{E}\{g_{kl}g_{kl}^H\} = \overline{g}_{kl}\overline{g}_{kl}^H + \beta_{kl}\mathbf{I}_N, \tag{6}$$

$$\psi_{kl} \triangleq \mathbb{E}\{z_{kl}z_{kl}^H\} = \tau_p\rho_p \sum_{i\in P_k}(\overline{g}_{il}\overline{g}_{il}^H + \beta_{il}I_N) + \sigma^2 I_N. \tag{7}$$

1. Energy Harvesting

During the wireless power transfer WPT, the anchor nodes can send their pilots and commands to the sensors. The transmitted symbols are coherent, in such a way that, they are transmitted with the same phase and the same power at the same time. In fact, there are two categories of the transmission which are; coherent and non-coherent. The transmitted signal, by an anchor node, can be expressed as;

$$x_l^E = \sum_{k=1}^{K} \sqrt{p_{kl}}\, w_{kl}^* s_k, \tag{8}$$

x_l is the transmitted signal by an anchor node and p_{kl} is the transmission power. W_{kl} is the weight vector. The transmitted power, sent by anchor node, should verify the following transmission limit;

$$P_l^E \triangleq \mathbb{E}\left\{\left\|x_l^E\right\|^2\right\} \leq \rho_d. \tag{9}$$

where E gives the expectation. P_d is the maximum transmission power. Linear minimum mean square error, LMMSE, as well as least square, LS, algorithms are applied. The average of transmitted power, sent by anchor node, can be modeled as follow;

$$P_l^E = \mathbb{E}\left\{\left\|\sum_{k=1}^{K} \sqrt{p_{kl}} w_{kl}^* s_K\right\|^2\right\} \overset{(a)}{=} \sum_{k=1}^{K} p_{kl} \mathbb{E}\{\|w_{kl}\|^2\} \tag{10}$$

$$\overset{(b)}{=} \begin{cases} \sum_{k=1}^{K} p_{kl} tr(\hat{R}_{kl}), & if\ LMMSE\ with\ w_{kl} = \hat{g}_{kl} \\ \sum_{k=1}^{K} p_{kl}\, tr(\psi_{kl}), & if\ LS\ with\ w_{kl} = z_{kl} \end{cases} \tag{11}$$

The average input power to the harvesting circuit, assuming *LMMSE* is applied, can be given by;

$$I_k = \mathbb{E}\left\{\left|\sum_{l=1}^{L}\sum_{i=1}^{K} \sqrt{p_{il}} w_{il}^H g_{kl} s_i\right|^2\right\}$$
$$\overset{(a)}{=} \sum_{l=1}^{L}\sum_{l'=1}^{L}\sum_{i=1}^{K} \sqrt{p_{il}}\sqrt{p_{il}}' \mathbb{E}\{w_{il}^H g_{kl} g_{kl'}^H w_{il'}\}$$
$$\overset{(b)}{=} \sum_{l=1}^{L}\sum_{i=1}^{K} p_{il} \mathbb{E}\{w_{il}^H g_{kl} g_{kl}^H w_{il}\}$$
$$+ \sum_{l=1}^{L}\sum_{\substack{l'=1 \\ l'\neq l}}^{L}\sum_{i=1}^{K} \sqrt{p_{il}}\sqrt{p_{il'}} \mathbb{E}\{w_{il}^H g_{kl}\}\mathbb{E}\{g_{kl'}^H w_{il'}\} \tag{12}$$

The average of input power values to the harvesting circuit, assuming *LS* is applied, can be given by;

$$I_k = \sum_{l=1}^{L}\sum_{i=1}^{K} p_{il} tr(\hat{R}_{il} R_{kl}) + \sum_{l=1}^{L}\sum_{i\in P_k} p_{il} s\tau_p^2 \rho_p^2 \times \left(2\beta_{kl}\Re\{\bar{g}_{kl}^H \psi_{il}^{-1} R_{il} \bar{g}_{kl} tr(R_{il}\psi_{il}^{-1})\} + \beta_{kl}^2 |tr(\psi_{il}^{-1} R_{il})|^2\right) + \sum_{l=1}^{L}\sum_{\substack{l'=1,\\ l'\neq l}}^{L}\sum_{i\in P_k} \sqrt{p_{il}}\sqrt{p_{il'}}\, \tau_p^2 \rho_p^2 \times \left(\bar{g}_{kl}^H \psi_{il}^{-1} R_{il} \bar{g}_{kl} + \beta_{kl} tr(\psi_{il}^{-1} R_{il})\right) \times \left(\bar{g}_{kl'}^H \psi_{il'}^{-1} R_{il'} \bar{g}_{kl'} + \beta_{kl'} tr(\psi_{il'}^{-1} R_{il'})\right)^* with\ LMMSE, \tag{13}$$

2. Uplink Information Transmission

The transmitted uplink information signal, r_l, can be given by;

$$r_l^I = \sum_{k=1}^{K} \sqrt{\eta_k} g_{kl} q_k + n_l^I, \quad l = 1, \dots, L, \tag{14}$$

The *SE* , R_k, can be calculated by the following relation;

$$R_k = \frac{\tau_u}{\tau_c} \log_2(1 + SINR_k), \tag{15}$$

The signal to interference plus noise ratio *SINR* can be calculated by the following relation;

$$SINR_k = \frac{\eta_k |a_k^H b_k|^2}{a_k^H (\sum_{i=1}^{K} \eta_i C_{ki}) a_k - \eta_k |a_k^H b_k|^2 + a_k^H D_k a_k} \tag{16}$$

3. Max-Min Fair Joint LSFD and Power Control

The power control aims to reduce the transmission uplink power whereas maximizing the total obtained uplink SE performance. The applied algorithm is as in

Modified Bisection Search for Max-Min Fair LSFD and Power Control
Initialization: Set $t_{\min} = 0$ and $t_{\max}$ as in respec- tively. Initialize a_k as all ones vector for $k = 1, \dots, K$.
while $t_{\max} - t_{\min} > \epsilon$ **do** ▷ $\epsilon > 0$ determines the solution accuracy.
Set $t = \frac{t_{\min}+t_{\max}}{2}$.
Solve the convex problem in without rank constraints and by taking $\{a_k\}$ and t as constant.
if feasible **then**
• Set the power control coefficients as the solution of this problem. ▷ the diagonal elements of the matrices $\{P_k\}$.
• Scale all the power control coefficients $\{p_{kl}\}$ and $\{\eta_k\}$ so that at least one of the constraints in respectively, are satisfied with equality.
• Obtain the optimum $\{a_k\}$ by maximizing each UE's SINR as a generalized Rayleigh quotient.
• Set $t_{\min} = t^\star$ and $t_{\max} = \lambda t^\star$ where $t^\star$ is the minimum of the SINRs after applying LSFD.
else
Set $t_{\max} = t$.
end if
end while
Output: Downlink power coefficients $\{p_{kl}\}$, uplink power coefficients $\{\eta_k\}$, LSFD vectors $\{a_k\}$, minimum SINR t.

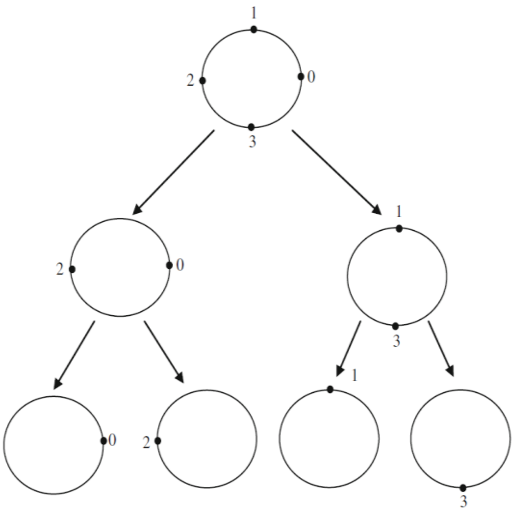
[39]. The power control algorithm is shown in Figure 1.

Figure 1: The power control algorithm [39].

IV. Trellis Coded Modulation

The TCM code can be used in order to provide correction capability of digital data "symbols" in a bandwidth efficient manner. The idea behind the TCM code is the arrangement of the encoded symbols, in such a way that, the Euclidean distance, among the subsequent symbols, can be largely increased. By increasing the separation distance among the successive symbols, the correction capability of the encoded data will be increased. Hence, the noise and fading immunity of the generated code and hence the communication data will be improved [40].

As example, the set partitioning scheme depends on partitioning the encoded data into smaller set. Each data set will be encoded to a symbol. The successive partition will be mapped to a symbol which is a way in its amplitude and phase from the previous one. By application of the set partitioning scheme, each symbol is far away from its neighboring symbols. The far distance can increase the correction capability of the code. Figure 2 shows the mapping process of a TCM code whereas Figure 3 displays the TCM encoder [40].



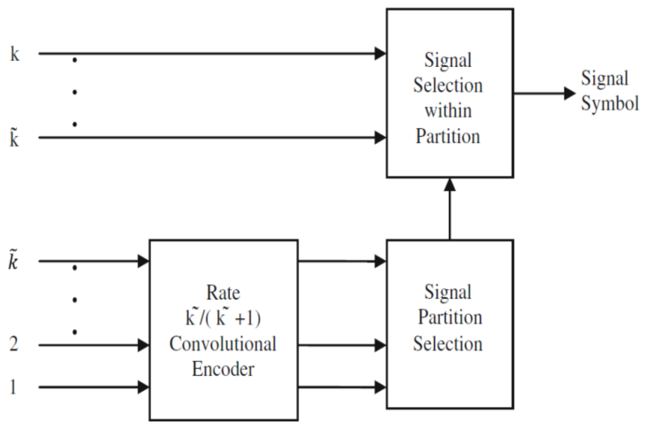


Figure 2: The mapping process of a TCM code [40].

Figure 3: The TCM encoder [40].

The TCM decoder can be carried out through application of the soft Viterbi decoder. The detection can be carried out according to the following steps;-

- Determine the best signal point within each subset by comparing the received signal to each of the signals allowed for a branch. The signal closest in distance to the received signal is considered as the best signal point and the corresponding branch metric is proportional to the distance between the best signal subset signal point and the received signal.
- The signal point is selected from each subset and its squared distance is the signal path through the code trellis that has the minimum sum of squared distances from the received sequence.

The TCM performance can be evaluated by a metric called asymptotic coding gain;

$$\text{Asymtotic coding gain} = \left(\frac{E_{\text{uncoded}}}{E_{\text{coded}}}\right)\left(\frac{d^2_{f/\text{coded}}}{d^2_{f/\text{uncoded}}}\right) \quad (17)$$

$E_{uncoded}$ refers to the normalized average received energy for an uncoded system.

E_{coded} refers to the normalized average received energy for a coded system.

$d_{f\ uncoded}^{2}$ refers to the square minimum free distance of an uncoded system.

$d_{f\ coded}^{2}$ refers to the square minimum free distance of a coded system.

V. Direct Diffusion Routing

This type of routing is based on interest which is a query that specifies what user wants. The sink node sends an interest to its neighbor nodes and that nodes receive the interest and send to its neighbors which known as diffusion process the gradient from the source back to the sink are setup when the event is sensed it is flowing from the originators of interests along multiple gradient path [41-45].

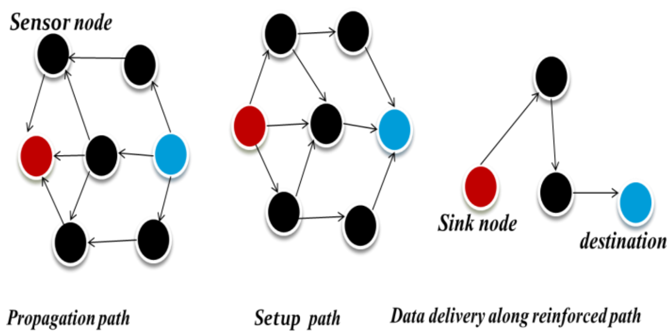


Figure 4: The direct diffusion routing algorithm.

VI. Simulation Results Direct Diffusion Routing

In this section, the simulation results are given and explained in details. The simulation parameters are concluded in Table 1. These parameters are chosen in order to be compatible with the previously carried out work which was in [39]. This compatibility can confirm the accuracy of the obtained results.

Table 1. The simulation parameters [39].

Parameter	Value
Carrier Frequency	3.4 GHz
Bandwidth	20 MHz
Modulation	4 State QPSK
Bit error rate “BER”	10^{-4}
Area	100 m×100m
Noise Variance	−96 dBm
Transmission Power	−40 dBm
τ_c	200
τ_p	5
τ_u	170
τ_d	25
Number of set up	500
Number of sensors	20
Anchors	36
Anchor Transmission	100 mW

Table 2 shows the min value of SE performance comparisons between the related work and the proposed work assuming coherent (C) and non-coherent transmission (NC) even for linear (L) or non-linear (NL). The proposed system applies both the TCM foe channel coding and the direct diffusion routing algorithm. The proposed system can offer higher SE performance than the previous one.

Table 3 presents the SE per user for the proposed system in comparable with the related work when linear minimum mean square error estimator is applied. It also can be observed that the proposed system can provide higher SE per user performance. From Tables 4, 5, and 6, it can be obvious that the proposed system can provide higher SE performance when it is compared with the related work.

Table 2. Min SE Performance comparisons with the related work assuming coherent and non-coherent transmission.

CDF	min SE per setup [b/s/Hz]				min SE per setup [b/s/Hz]			
	MMF-NC-NL	MMF-NC-L	MMF-C-NL	MMF-C-L	MMF-NC-NL	MMF-NC-L	MMF-C-NL	MMF-C-L
0	0.6	0.6	1.25	1.5	2.466	2.466	5.138	6.165
0.2	1.5	1.5	2.1	2.25	6.165	6.165	8.631	9.248
0.4	1.75	1.75	2.25	2.3	7.193	7.193	9.248	9.453
0.6	1.9	1.9	2.4	2.5	7.809	7.809	9.864	10.28
0.8	2.1	2.2	2.5	2.6	8.631	9.042	10.28	10.69
1	2.5	2.5	2.75	2.75	10.28	10.28	11.3	11.3

Table 3. SE Performance comparisons with the related work assuming LMMSE application.

CDF	SE per User [b/s/Hz]-LMMSE		SE per User [b/s/Hz]-LMMSE	
	L= 36, N=16, NC	L= 36, N=16, C	L= 36, N=16, NC	L= 36, N=16, C
0	1.5	2.1	6.165	8.631
0.2	2.7	3.2	11.097	13.152
0.4	2.9	3.4	11.919	13.974
0.6	3.1	3.45	12.741	14.1795
0.8	3.2	3.6	13.152	14.796
1	3.5	3.8	14.385	15.618

Table 4. SE Performance comparisons with the related work coherent and non-coherent transmission.

CDF	SE per User [b/s/Hz]-LMMSE		SE per User [b/s/Hz]-LMMSE	
	L= 36, N=16, NC	L= 36, N=16, C	L= 36, N=16, NC	L= 36, N=16, C
0	0.25	0.75	1.0275	3.0825
0.2	1.25	1.9	5.1375	7.809
0.4	1.5	2.25	6.165	9.2475
0.6	1.75	2.4	7.1925	9.864
0.8	2	2.55	8.22	10.4805
1	2.6	3	10.686	12.33

Table 5. SE Performance comparisons for different pilot lengths.

CDF	SE per User [b/s/Hz]				SE per User [b/s/Hz]			
	Shared τ_p=5	Random τ_p=5	Shared τ_p=10	Random τ_p=10	Shared τ_p=5	Random τ_p=5	Shared τ_p=10	Random τ_p=10
0	1	1	1.75	1.75	4.11	4.11	7.1925	7.1925
0.2	2.2	2.2	2.4	2.4	9.042	9.042	9.864	9.864
0.4	2.3	2.3	2.55	2.55	9.453	9.453	10.4805	10.4805
0.6	2.4	2.4	2.6	2.6	9.864	9.864	10.686	10.686
0.8	2.5	2.5	2.7	2.7	10.275	10.275	11.097	11.097
1	2.8	2.8	3.1	3.1	11.508	11.508	12.741	12.741

Table 6. SE Performance comparisons with the related work assuming LMMSE application for different values of data periods.

CDF	SE per setup [b/s/Hz]-LMMSE			SE per setup [b/s/Hz]-LMMSE		
	τ_d=15	τ_d=25	τ_d=45	τ_d=15	τ_d=25	τ_d=45
0	1.5	1.5	1.5	6.165	6.165	6.165
0.2	2.1	2.2	2	8.631	9.042	8.22
0.4	2.25	2.25	2.2	9.2475	9.2475	9.042
0.6	2.3	2.35	2.25	9.453	9.6585	9.2475
0.8	2.4	2.5	2.35	9.864	10.275	9.6585
1	2.85	2.85	2.6	11.7135	11.7135	10.686

VII. CONCLUSION

A WSN is designed for monitoring the radiometry in free space. The proposed WSN can provide a lot of advantages than previous. These advantages included increasing the harvested energy for the sensors through application of synchronous transmission. Moreover, the SE of the uplink transmission data was maximized through transmission over high reliable links. The power control was applied in order to optimize the transmission power. In conclusion, the application of power control could improve the SE performance of a WSN. In addition, the synchronous energy harvesting could improve the total harvested power at the sensors.

Declarations

- The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.
- Funding source of this work is supported by the faculty of Electronic Engineering, Menoufia University, Menouf, Egypt.
- There is no conflict between this work and other published work.
- The Matlab code is available on reasonable request.

Appendix

Appendixes, if needed, appear before the acknowledgment.

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