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Age of information in wireless powered IoT networks: NOMA vs. TDMA

Hosein Azarhava, Mehran Pourmohammad Abdollahi, Javad Musevi Niya*

WiLab, Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, East Azerbaijan, Iran

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ABSTRACT

In this paper we consider a wireless IoT network with energy harvesting sensors and finite battery capacity which obtain their energy from a wireless power transmitter and communicates with a fusion center. We study a specific system model in which one of the sensors with higher battery capacity performs as a central node and obtains the main data from the environment while the other sensors observe the variations of data. Since, fusion center needs fresh data in real time applications and old useless data would be discarded, thus, the Age of Information (AoI) can be considered as one of the major parameters for such networks. In the present paper, we proposes a new protocol based on NOMA and we obtain a closed-form equation for the age of information for whole network. Then, we optimize the age of information on power schedule parameter. As well, the age of whole network is calculated for the same network under TDMA protocol and is optimized on time fraction parameter. Finally, the numerical results are obtained for several parameters and the optimized parameters are applied to compare the age under both protocols. The results show that using NOMA will improve AoI performance compared to TDMA scheme.

1. Introduction

Increasing use of IoT networks has resulted in developing the advanced sensors with capability of absorbing energy from different resources which enables the manufacturing very small devices with finite battery sizes. The concept of wireless energy transmission first has been introduced in Varshney [1] and has been investigated in different networks where the system performance is analyzed under the corresponding conditions imposed to the network such as [2] and [3]. As the number of connected sensors grows in such networks, the access to the scarce shared spectrum becomes a great challenge specially, in real time applications which process the received update data to transfer control messages instantly [4]. Hence, a demand to fresh data is exposed in these applications such as health care, industrial monitoring and etc. The freshness of data can be measured by the concept called age of information which was introduced in Kaul et al. [5], where it is defined as the difference between generation time and successful delivery of a packet to a destination. The concept is comprehensively explained in Kosta et al. [6].

Since status update is a crucial parameter in some applications, AoI has to be taken to account in calculations of system performance. AoI is the case of study in Ni et al. [7] for Internet of Vehicular (IoV) communications where beacon broadcasting is scheduled in terms of vehicular density parameter considering AoI. Also, the correlation of data between the source nodes is used to achieve optimal use of updates in the network in order to increase the network life time [8]. In cognitive radio networks, Channel State Information (CSI) has to be available for transmitters to improve the system performance; for time-variant channels, fresh CSI enhances the system parameters considering the bounds for staleness of data in the network [9]. Despite [7–9], scheduling policies in Kadota et al. [10] and packet management in Costa et al. [11] are proposed to investigate AoI as the main parameter of the network. Likewise, fresh data has been considered as a constraint on optimizing energy efficiency in Valehi and Razi [12]. A novel approach to calculate AoI can be obtained using deadline counter in the packet which optimizes the system performance for M/M/1/1 and M/M/1/2 queues [13]. The effect of network coding in multicast networks [14] improves AoI with fixed block size codes while AoI increases with the number of users. Also, a UAV assisted network is considered in Abd-Elmagid and Dhillon [15] to send

* Corresponding author.
E-mail addresses: azarhava@tabrizu.ac.ir (H. Azarhava), mehran.pour@tabrizu.ac.ir (M. Pourmohammad Abdollahi), niya@tabrizu.ac.ir (J. Musevi Niya).

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status update to a destination where the average peak of AoI is minimized for an optimized trajectory of the UAV.

The constraints of energy harvesting process have been applied in Arafa and Ulukus [16], Wu et al. [17], Arafa et al. [18] to calculate age of information for different networks. Age-minimal transmission in Arafa and Ulukus [16] has been achieved in a relaying network considering the delay which is caused due to arrivals of energy packets to the harvesting nodes. The authors in Wu et al. [17] design an optimal online policy for a monitoring sensor to send update status of a system to a destination where the time average AoI is achieved for different battery sizes. However, the same subject has been investigated in Arafa et al. [18] and Arafa et al. [19] for random battery recharges and finite battery sizes, respectively.

The authors in Dong et al. [20] study AoI in a two-way communication in which a master node transfers data and energy to a slave node and the average uplink AoI is derived in terms of downlink data rate. However, Krikidis [21] has studied AoI in a simple wireless powered sensor network consisting of a sensor, an information receiver and a separated wireless power transmitter in which AoI is calculated in closed form expressions and it is optimized on the capacity of sensors battery size considering the design of power transmitter. As one of the rare works which investigates AoI under NOMA, Ali Maatouk studies AoI comparing OMA and NOMA without energy harvesting nodes for spectral efficiency multiplication factor and arrival rates of the users [22]. The results of [22] show that achieving better performance for AoI depends on the condition of the problem. They came to the result that superiority of the age of information in NOMA and OMA setting depends on spectral multiplication factor ($1 < \alpha < 2$). In low α ($1 < \alpha < 1.28$) the performance of OMA is better than NOMA, but when the increase in spectral multiplication factor is really high, NOMA has the potential of outperforming OMA. Unlike [23] as an extension of wireless powered IoT networks with M sensors which maximizes available throughput under energy consumption conditions for NOMA and TDMA schemes, we investigate AoI in a similar network equipped with an auxiliary channel which collects CSI and the sensors' battery status. Then, we derive the closed form expressions for NOMA and TDMA scenarios; Also, we optimize AoI under power and time schedule parameters for both mentioned schemes considering different power transmitter values. The main contribution of this paper is summarized as follows: (1) We propose a new system model for wireless powered IoT networks which uses an auxiliary channel to exchange CSI between fusion center and sensors and obtain their battery statuses; (2) The closed form expressions are derived for AoI under NOMA and TDMA scenarios; (3) AoI is minimized through an optimization problem under power and time schedule parameters for NOMA and TDMA schemes, respectively.

The rest of the paper is organized as follows: in Section 2 the system model is proposed and in Section 3, AoI formula is obtained and optimized for NOMA and TDMA schemes. Numerical results are shown in Section 4. Finally, the paper is concluded in Section 5.

2. System model

We consider a wireless powered IoT system model in which M wireless peripheral sensors distributed around a Central Node (CN), transmitting their data to a fusion center (FC) during each time slot (Fig. 1). The main data is measured by CN while the minor data can be observed via the surrounding peripheral sensors which are chosen by a coordinator using additional data corresponding to each sensors' batteries. As a practical example, suppose that the central node transmits some parameters of a phenomena/event (such as heat, humidity and etc.) in a given point while some other sensors measure the effect of this phenomena/event (such as

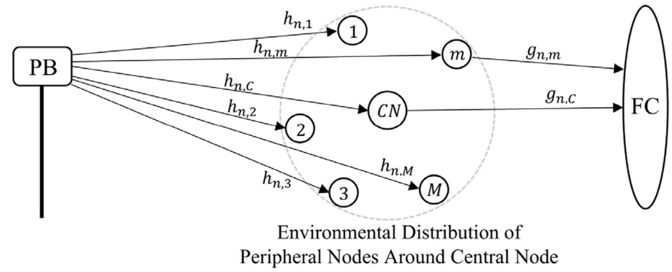

Fig. 1. IoT Sensor Network.

smoke, height of liquid in a reservoir and etc.) in surrounding environment; However, these surrounding nodes would act as confirming devices to increase the reliability of the network. Our model is the evaluation of such systems where the peripheral nodes transmit additional data besides the main data which is transmitted by CN. A useful data unit can be shown as a pair of (D_C, D_m) which shows the CNs data and sensor ms data ($m = 1, 2, M$). The data pair (D_C, D_m) is achieved right after both data are successfully transmitted to the FC at the end of that time slot otherwise the FC discards the received incomplete data. On the other word, the mentioned property of such networks enables us to avoid the side information about the sensors emphasizing that FC needs only one of the lateral sensors data in addition to CNs data to update itself. All sensors are capable of energy harvesting via a Power Beacon (PB) [3] which transmits the wireless power during each time slot with transmission power equal to P_E. Then, in the next time slot, all of the peripheral sensors will have the chance to send their data to FC if they have been fully charged in the previous time and are chosen by the coordinator. We assume that data and power are transferred in different frequencies simultaneously. Thus, the sensors are capable of transmitting data and charging their battery at the same time slot. In the other words, each sensor harvests energy periodically while it transmits its data to FC. The line of sight increases the efficiency of energy reception in harvesting sensors but in some IoT networks which use indoor sensors or embedded sensors inside of the materials, the effect of line of sight is eliminated and the scattered power signals arrive via non-line of sight paths. As a result, the fading over the wireless channels between PB and the harvesting devices could be considered Rayleigh instead of Rician. Such an assumption has been considered in Krikidis [21]. Thus, all wireless links between PB and sensors and also between sensors and FC is assumed to be Rayleigh fading channels. The channel gains between PB and each sensor including CN are denoted by $h_{n,m}$ and $h_{n,C}$ and also the channel gains between each sensor including CN and FC are denoted by $g_{n,m}$ and $g_{n,C}$, respectively. As well, we assume flat fading for each channel i.e. the channel gain is fixed over each time slot but it can change from one to another.

PB is equipped with an omnidirectional antenna which transmits power to the single antenna sensors. Considering each time slot equal to unit time interval ($T = 1$), the harvested energy by each sensor is as follows

$$E_{H,m} = T\eta_m h_{n,m} P_E = \eta_m h_{n,m} P_E \tag{1}$$

$$E_{H,C} = T\eta_C h_{n,C} P_E = \eta_m h_{n,C} P_E \tag{2}$$

where $\eta_m \in (0, 1]$ and $\eta_C \in (0, 1]$ are the sensors and CNs battery charging ratio, respectively; However, it is supposed that the effect of noise in harvesting phase is negligible compared to that of PBs transmission power. We assume that if the harvested energy by sensor and CN is greater than a given threshold, γ_0 and γ_C, the batteries will be fully charged, otherwise, the battery discards the incoming energy packet during that time slot. Also, we consider that the batteries of the sensors and CN have been provided with a buffer [24] equal to B_m and B_c, respectively ($B_c > B_m$). We assume that the wireless power is transferred via quantized energy packets with the power equal to P_E. The battery in each sensor consists of a capacitor with a capacity of unit energy charged to γ_0 or γ_c. The sensor transmits data if its battery has complete energy, on the contrary, the energy is consumed to update its status with fresh data [25]. Since, the fading over all channels is assumed to be Rayleigh, $h_{n,m}$ and $h_{n,c}$ have exponential distributions i.e. $h_{n,m} \sim \exp(\lambda_{h,m})$ and $h_{n,c} \sim \exp(\lambda_{h,C})$. Thus, the probabilities of the successful power signal reception in the sensor m and CN are given by

$$\rho_m = Pr(\text{energy packet is successfully received in sensor } m)$$
$$= Pr\{\eta_m h_{n,m} P_E > \gamma_0\} = e^{\frac{-\gamma_0 \lambda_{h,m}}{\eta_m P_E}} \tag{3}$$

and

$$\rho_C = Pr(\text{energy packet is successfully received in CN})$$
$$= Pr\{\eta_C h_{n,C} P_E > \gamma_0\} = e^{\frac{-\gamma_0 \lambda_{h,C}}{\eta_C P_E}} \tag{4}$$

We consider $\lambda_{h,C} = 10^3 D_c^\theta$ and $\lambda_{h,m} = 10^3 D_m^\theta$ where D_c and D_m are the distance between PB and CN and the distance between PB and sensor m, respectively, and θ shows the path loss coefficient in that area [23]. Obviously, a battery is not being charged with probability $1 - \rho_m$ and the central node will be empty with probability $1 - \rho_C$. Likewise, a sensor is discharged during data transmission or equivalently consumes one packet during any transmission if its battery has been charged to one in previous time interval and it is chosen to participate in data transfer. Considering these probabilities, a sensor will transmit its data with rate R_m if its battery saves one packet and it is chosen for transmission. However, it will remain silent if charging process does not meet the required threshold or it is not allowed to transmit data even the battery has enough energy.

The information about the sensors' battery status and CSI are transmitted to FC via an auxiliary channel so that FC could make a decision on choosing a sensor to send additional data. The selecting algorithm could be a random process, a permutation using Round Table algorithm or MAC protocols which use a contention window to acquire users' data and etc. To avoid the increasing of complexity, FC chooses one of the sensors randomly. The other selection algorithms will be considered in the future work.

3. Age of information calculations

Freshness of data is a crucial parameter in some IoT networks such as health care applications or controlling processes where some temperature or pressure indicators need to be reported as soon as possible so that the FC could make a right decision instantly. This means that the FC would take an incorrect action due to lack of fresh data which arrives later than a specific time. In such cases, we need to decrease the age of data packets or use protocols with low AoI parameter in order to avoid the wrong decisions in the FC. The instantaneous age of information for data pair (D_C, D_m) is defined at the end of time slot n as below

$$A_n^{(C,m)} = n - G_n^{(C,m)} \tag{5}$$

where $G_n^{(C,m)}$ denotes the time that the data is generated by CN and sensor m.

It is assumed that a sensor does not generate new data until its current data is delivered to the FC successfully. Whenever the data is delivered, new data can be generated in that sensor to be transmitted. Thus, the age for new packets is reset to one [21] for pair (D_C, D_m) after packets delivery. The timing process in Fig. 2 shows the AoI evolution for the pair (D_C, D_m) in the considered system model. Since only the batteries' side information are available at the coordinator, in each time slot, one of the sensors with full battery is randomly chosen to transmit its data. Therefore, in all time slots which sensor m is not successful, it is possible for the other charged sensors to transmit their data to FC and AoI would be updated for the other corresponding pairs of (D_C, D_i) for $i \neq m$. It can be considered that the sensor can call off a packet passes a maximum tolerable age to avoid reaching infinite ages. However, the age is increased by one until no successful transmission is achieved by both CN and sensor m. We propose a new method for data transfer in the network in which we assume that the central node with higher battery hence with higher transmission power always sends its data if it has enough energy, whereas the other sensors can be scheduled to send data based on NOMA or TDMA system. That is the successful packet transmission occurs in time slot n if CNs battery status and at least one of the sensors battery status are fully charged with probability ρ_C and ρ, respectively, and the data transmission meets the required SNR on the FC side. The time between two consecutive successful transmissions for pair (D_C, D_m) is denoted by a discrete random variable $T_j(m)$ in which $1 \leq T_j(m) \leq \infty$.

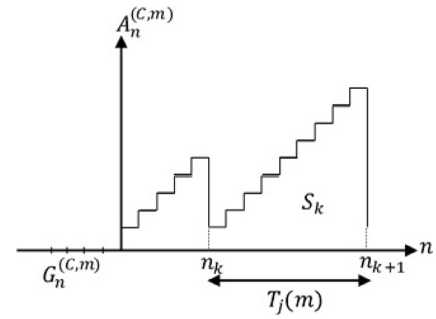

Fig. 2. Age of Information for sensor m of network.

The average age of information for data pair (D_C, D_m) can be defined as K successful transmission in N time slot while N tends to infinity. Thus, from [21] we have

$$\Delta_n^{(C,m)} = \lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} A_n^{(C,m)} = \lim_{N\to\infty} \frac{1}{N} \sum_{k=1}^{K} S_k = \lim_{N\to\infty} \frac{K}{N} \frac{1}{K} \sum_{k=1}^{K} S_k \tag{6}$$

where S_k is the area covered by the age curve in k^{th} successful transmission and is equal to $\frac{T_j(m)(T_j(m)+1)}{2}$. It is implied that $\lim_{N\to\infty} \frac{N}{K(N)}$ denotes the average of successful transmission time $E[T_j(m)]$ and $E[S] = \lim_{N\to\infty} E[S_k]$ whereas $E[S_k] = \frac{1}{K}\sum_{k=1}^{K} S_k$. Thus, the Eq. (6) from [21] can be rewritten as

$$\Delta_n^{(C,m)} = \frac{E[S]}{E[T_j(m)]} = \frac{E[\frac{T_j(m)(T_j(m)+1)}{2}]}{E[T_j(m)]} = \frac{E[T_j^2(m)] + E[T_j(m)]}{2E[T_j(m)]} \tag{7}$$

To calculate $E[T_j(m)]$, we have to obtain the probability of being successful in time slot j, $Pr\{T_j(m)\}$, while $j-1$ time slots have been wasted due to unsuccessful transmissions.

$$\begin{aligned} E[T_j(m)] &= \sum_{T_j(m)=1}^{\infty} T_j(m) Pr\{T_j(m)\} \\ &= \sum_{T_j(m)=1}^{\infty} T_j(m) P_{suc} (1-P_{suc})^{T_j(m)-1} \\ &= \frac{P_{suc}}{(1-P_{suc})} \sum_{T_j(m)=1}^{\infty} T_j(m)(1-P_{suc})^{T_j(m)} \end{aligned} \tag{8}$$

where $P_{suc}^{(D_C,D_m)}$ has been briefed to P_{suc} to simplify the notations and the corresponding protocol will be added to the index of

P_{suc} later. Also, the second momentum of $T_j(m)$ could be computed as

$$E[T_j^2(m)] = \sum_{T_j(m)=1}^{\infty} T_j^2(m) Pr\{T_j(m)\} = \sum_{T_j(m)=1}^{\infty} T_j^2(m) P_{suc}(1-P_{suc})^{T_j(m)-1} = \frac{P_{suc}}{(1-P_{suc})} \sum_{T_j(m)=1}^{\infty} T_j^2(m)(1-P_{suc})^{T_j(m)} \quad (9)$$

Proposition 1. *The average of consecutive successful transmissions denoted by $E[T_j(m)]$, is equal to*

$$E[T_j(m)] = \frac{1}{P_{suc}^{(D_C,D_m)}} \quad (10)$$

Proof: Considering the equation $\sum_{k=1}^{\infty} kx^k = \frac{x}{(1-x)^2}$ for $0 < x < 1$ from [26], the Eq. (8) is calculated by substituting $k = T_j(m)$ and $x = 1 - P_{suc}^{(D_C,D_m)}$.

Proposition 2. *The average of squared consecutive successful transmissions, $E[T_j^2(m)]$, is equal to*

$$E[T_j^2(m)] = \frac{2 - P_{suc}^{(D_C,D_m)}}{(P_{suc}^{(D_C,D_m)})^2} \quad (11)$$

Proof: Calculating the derivative of equation in proof of proposition 1, since we have $\sum_{k=1}^{\infty} k^2x^k = \frac{x(1+x)}{(1-x)^3}$ for $0 < x < 1$ then the Eq. (9) is calculated by substituting $k = T_j(m)$ and $x = 1 - P_{suc}^{(D_C,D_m)}$.

Thus, the average age of information for data pair (D_C, D_m) can be simplified as

$$\Delta_n^{(C,m)} = \frac{1}{P_{suc}^{(D_C,D_m)}} \quad (12)$$

Now, the average age of information for whole network can be calculated as

$$AoI = \frac{1}{M}\sum_{m=1}^{M} \Delta_n^{(C,m)} = \frac{1}{M}\sum_{m=1}^{M} \frac{1}{P_{suc}^{(D_C,D_m)}} \quad (13)$$

3.1. AoI using NOMA scheme

In this case, the sensors make use of power-based NOMA in which one of the sensors can transmit its data simultaneously with CN if the charging process has been accomplished. The signal received by FC in each time slot sent by central node and sensor m is as follows

$$y_n(t) = \sqrt{P_C} g_{n,c}(t) X_c(t) + \sqrt{P_m} g_{n,m}(t) X_m(t) + n_n(t) \quad (14)$$

where P_C and P_m are CN and sensor m transmission powers with constant sum i.e. $P_C = \alpha P_T$ and $P_m = (1-\alpha)P_T$ with $0.5 < \alpha < 1$ $(P_C > P_m)$ where α denotes the power schedule parameter, $X_c(t)$ and $X_m(t)$ are the signals sent by CN and sensor m with $E[|X_c(t)|^2] = 1$ and $E[|X_m(t)|^2] = 1$, respectively, $g_{n,c}(t)$ and $g_{n,m}(t)$ are the effect of Rayleigh fading with exponential distribution $g_{n,c}(t) \sim \exp(\lambda_{g,c})$ and $g_{n,m}(t) \sim \exp(\lambda_{g,m})$ where $\lambda_{g,c} \geq \lambda_{g,m}$ due to better channel condition between CN and FC. As well, $n_n(t)$ is the circularly symmetric complex Gaussian (CSCG) noise on the link between sensor m and FC. Also, it is assumed that it is independent and identically distributed (i.i.d) random process with zero mean and variance $E[|n_n(t)|^2] = \sigma_n^2$. We suppose that the receiver side in the FC uses an ascending order Successive Interference Cancelation (SIC) [27] to extract the correct data from received signal. Since, the transmission power of CN is greater than sensor m, then using SIC, the receiver can subtract the signal sent by sensor m while the CNs signal is treated as noise in decoding sensor ms signal. We define the successful packet delivery on condition that the transmission rate corresponding to channel SNR is greater than a given minimum amount. Then, we have

$$R_{CN} > R_C \;\Rightarrow\; \tau \log_2(1+\gamma_{n,C}) > R_C$$
$$R_m > R_0 \;\Rightarrow\; \tau \log_2(1+\gamma_{n,m}) > R_0 \quad (15)$$

where τ represents the time fraction for transmission, $\gamma_{n,C} = \frac{\alpha P_T g_{n,c}}{\sigma_n^2}$ is the SNR over the link between CN and FC and $\gamma_{n,m} = \frac{(1-\alpha)P_T g_{n,m}}{(\sigma_n^2 + \alpha P_T g_{n,c})}$ is the SINR over the link between sensor m and FC. R_C is the minimum threshold rate received from CN and R_0 is the minimum threshold rate received from sensor m with assumption that $R_c \geq R_0$. Since both CN and sensor m transmit their data within a time slot, then, $\tau = 1$.

To obtain a successful transmission for data pair (D_C, D_m) in time slot n, three conditions must be satisfied simultaneously. First of all, CN and the sensor m have to be fully charged and second, the SNR on the receiver side has to satisfy the equations in (15). However, the first condition imposes several states on the system. That is the probability of choosing sensor m in each time slot depends on the number of surrounding sensors with full battery. Thus, it is the union of all possible probabilities that one or two or generally k sensors from M sensors have enough charges to send data whereas sensor m is chosen among them. Therefore, considering that CN is fully charged and the sensor m is chosen, the probability of successful transmission for data pair (D_C, D_m) in time slot n, can be defined as follows

$$P_{suc}^{(D_C,D_m)}(n,m) = Pr\{\text{Both CN and the fully charged sensor } m \text{ is chosen } \cap \text{Event}(R_{CN} > R_C) \cap \text{Event}(R_m > R_0)\} \quad (16)$$

Since, all conditions in Eq. (16) are independent of each other, the Eq. (16) is calculated as follows

$$P_{suc}^{(D_C,D_m)}(n,m) = Pr\{\text{CN is fully charged}\} Pr\{m\} Pr\{R_{CN} > R_C\} Pr\{R_m > R_0\} \quad (17)$$

where $Pr\{m\}$ shows the probability of choosing sensor m which has harvested enough energy. To find $Pr\{m\}$, first we define two separated sets $B_{\ni m}$ and $B_{\not\ni m}$ where $B_{\ni m}$ shows all the possible events of charged sensors, including sensor m and $B_{\not\ni m}$ is its complementary, Then, the probability of $Pr\{m\}$ can be written as

$$Pr\{m\} = P(m|B_{\ni m})P(B_{\ni m}) + P(m|B_{\not\ni m})P(B_{\not\ni m}) \quad (18)$$

It is inferred that $B_{\ni m}$ consists of disjoint events exhibiting the charged sensors, i.e. $B_{\ni m} = \bigcup_{k=1}^{M} B_{k\ni m}$ where $B_{k\ni m}$ shows that there are exactly k fully charged sensors including m. Then, we have

$$P(B_{\ni m}) = P\left(\bigcup_{k=1}^{M} B_{k\ni m}\right) = \sum_{k=1}^{M} P(B_{k\ni m}) \quad (19)$$

To calculate AoI for sensor m, we know that its battery is full which results in $P(m|B_{\not\ni m}) = 0$. Considering that $P(m|B_{\ni m}) = \frac{1}{k}$ (which is the probability of choosing sensor m among k sensors), the Eq. (18) is simplified as

$$Pr\{m\} = \frac{1}{k}\sum_{k=1}^{M} P(B_{k\ni m}) \quad (20)$$

From the definition of $B_{k\ni m}$, it is implied that $k-1$ sensors can be charged besides sensor m with different permutations equal to $\binom{M-1}{k-1}$. Thus,

$$P(B_{k\ni m}) = \sum_{l=1}^{\binom{M-1}{k-1}} P(B_{k\ni m,l}) \quad (21)$$

where $P(B_{k\ni m,l})$ is the l^{th} permutation of k charged sensors including sensor m. Then, $Pr\{m\}$ can be rewritten as

$$Pr\{m\} = \frac{1}{k}\sum_{k=1}^{M}\sum_{l=1}^{\binom{M-1}{k-1}} \prod_{\substack{i\in B_{k\ni m,l}\\ (charged)}} \rho_i \prod_{\substack{j\in B_{k\ni m,l}\\ (uncharged)}} (1-\rho_j) \tag{22}$$

We explain these combinations by an example for $M=4$ sensors and sensor $m=2$ is charged completely.

$$\begin{aligned} Pr\{2\} &= \rho_2(1-\rho_1)(1-\rho_3)(1-\rho_4) + \frac{1}{2}\rho_2[\rho_1(1-\rho_3)(1-\rho_4) \\ &+ \rho_3(1-\rho_1)(1-\rho_4) + \rho_4(1-\rho_1)(1-\rho_3)] \\ &+ \frac{1}{3}\rho_2[\rho_1\rho_3(1-\rho_4) + \rho_1\rho_4(1-\rho_4) + \rho_3\rho_4(1-\rho_1)] \\ &+ \frac{1}{4}\rho_2\rho_1\rho_3\rho_4 \end{aligned}$$

If k shows the number of fully charged sensors among M sensors, considering Eqs. (3), (4), (15) and (22), the Eq. (17) is calculated as

$$\begin{aligned} P^{(D_C,D_m)}_{suc,NOMA}(n,m) &= Pr\left\{\log_2(1+\frac{\alpha P_T g_{n,C}}{\sigma_n^2}) > R_C\right\} \\ &\times Pr\left\{\log_2\left(1+\frac{(1-\alpha)P_T g_{n,m}}{\sigma_n^2+\alpha P_T g_{n,C}}\right) > R_0\right\}\rho_C Pr\{m\} \end{aligned} \tag{23}$$

Considering that $g_{n,m}$ and $g_{n,C}$ are independent of each other and $A = 2^{R_0}-1$, then the second probability in Eq. (23) is calculated as (24); then substituting Eq. (24) in (23), the probability of successful transmission can be written as (25), where $B = 2^{R_c}-1$.

$$\begin{aligned} &Pr\left\{\log_2\left(1+\frac{(1-\alpha)P_T g_{n,m}}{\sigma_n^2+\alpha P_T g_{n,C}}\right) > R_0\right\} \\ &= Pr\left\{g_{n,m} - \frac{A\alpha}{(1-\alpha)}g_{n,c} > \frac{A\sigma_n^2}{(1-\alpha)P_T}\right\} \\ &= \int_{\frac{A\sigma_n^2}{(1-\alpha)P_T}}^{\infty}\int_0^{\frac{(1-\alpha)P_T g_{n,m}-A\sigma_n^2}{A\alpha P_T}} \lambda_{g,m}\lambda_{g,C}e^{-\lambda_{g,C}g_{n,C}}e^{-\lambda_{g,m}g_{n,m}}dg_{n,C}dg_{n,m}\} \\ &= e^{-\frac{A\lambda_{g,m}\sigma_n^2}{(1-\alpha)P_T}}\left(\frac{\lambda_{g,C}(1-\alpha)}{\lambda_{g,m}A\alpha+\lambda_{g,C}(1-\alpha)}\right) \end{aligned} \tag{24}$$

$$\begin{aligned} P^{(D_C,D_m)}_{suc,NOMA}(n,m) &= (e^{-\frac{B\lambda_{g,C}\sigma_n^2}{\alpha P_T}})\left\{e^{-\frac{A\lambda_{g,m}\sigma_n^2}{(1-\alpha)P_T}}\left(\frac{(1-\alpha)}{\frac{\lambda_{g,m}}{\lambda_{g,C}}A\alpha+(1-\alpha)}\right)\right\} \\ &\times \rho_C Pr\{m\} \end{aligned} \tag{25}$$

Now, the average age of information for NOMA system is

$$AoI_{NOMA} = \frac{1}{M}\sum_{m=1}^{M}\frac{1}{P^{(D_C,D_m)}_{suc,NOMA}(n,m)} \tag{26}$$

3.2. AoI optimization problem for NOMA scheme

We want to calculate the power schedule parameter α so that the AoI is minimized. Therefore, the optimization problem can be considered as

$$\begin{aligned} &\min_{\alpha} \quad AoI_{NOMA} \\ &s.t \quad 0.5 < \alpha < 1 \end{aligned} \tag{27}$$

Since $P^{(D_C,D_m)}_{suc,NOMA}(n,m)$ is independent for different sensors, optimization problem in (27) is equivalent to maximize $P^{(D_C,D_m)}_{suc,NOMA}(n,m)$ individually. Therefore the optimization problem in (27) could be changed to

$$\begin{aligned} &\max_{\alpha}\{P^{(D_C,D_m)}_{suc,NOMA}(n,m)\} \\ &s.t \quad 0.5 < \alpha < 1 \end{aligned} \tag{28}$$

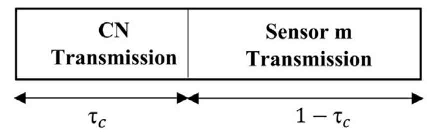

Fig. 3. TDMA schedule.

First, we rewrite the object function as multiply of two separate function, $F_o(\alpha) = H(\alpha)G(\alpha)$, where $H(\alpha) = e^{\frac{-B'}{\alpha}}e^{\frac{-A'}{1-\alpha}}$, $G(\alpha) = \frac{1-\alpha}{1+(A''-1)\alpha}$, $A' = \frac{A\lambda_{g,m}\sigma_n^2}{P_T}$, $B' = \frac{B\lambda_{g,C}\sigma_n^2}{P_T}$ and $A'' = \frac{\lambda_{g,m}}{\lambda_{g,C}}A$. Knowing that $\lim_{\alpha\to 0,1}F_o(\alpha) = 0$ and $F_o(\alpha) > 0$ for all $0 < \alpha < 1$, we conclude that $F_o(\alpha)$ has at least one maximum point in $\alpha \in (0,1)$. The parameters A' and B' are positive random variables, hence, $H(\alpha)$ is a positive function, and it has only one maximum point in $\alpha = 0.5$ for $A' = B'$. But for $A' \neq B'$, we need to calculate α from equation $H'(\alpha) = 0$ which yields the maximum points of $H(\alpha)$ as bellow

$$\alpha_H = \frac{1\pm\sqrt{\frac{A'}{B'}}}{1-\frac{A'}{B'}} \tag{29}$$

To approach a real model, we consider $\lambda_{g,c} = 10^3 d_C^{\theta}$ and $\lambda_{g,m} = 10^3 d_m^{\theta}$ where d_C and d_m are the distance between CN and FC and the distance between sensor m and FC, respectively, and θ shows the path loss coefficient in that area. Since CN and sensors are close to each other compared to their distance from FC, we can assume that $d_c \simeq d_m$ which yields $\lambda_{g,C} \simeq \lambda_{g,m}$. Now, by considering $R_c > R_0$ we obtain $A' < B'$; It can be seen that for all $A' < B'$, only one of the roots of $H'(\alpha) = 0$ belongs to the interval (0.5,1) which satisfies the condition considered for α. As a result, $H(\alpha)$ has only one maximum point for $\alpha \in (0.5, 1)$. Likewise, A'' is positive random variable, thus, $G'(\alpha) = \frac{-A''}{[1+(A''-1)\alpha]^2}$ is negative for all α which means $G(\alpha)$ is strictly decreasing function of α. We see that $F_o(\alpha)$ is the multiply of two homographic and exponential functions so that for $0.5 < \alpha < 1$, the homographic function, $G(\alpha)$, is always decreasing whereas the exponential function is ascending before its maximum and is decreasing after its maximum. We know that the increasing effect of an exponential function predominates the decreasing effect of a homographic function, that is, $G(\alpha)$ does not change the behavior of $H(\alpha)$. Therefore, $F_o(\alpha)$ has only one maximum point, $\alpha_{\max}$, and the effect of homographic function causes $\alpha_{\max}$ to move within interval (0.5,1). As a result, $\alpha_{\max}$ can be calculated via equation $F_o'(\alpha) = 0$ which yields

$$\frac{1-\alpha}{1+(A''-1)\alpha}\left[\left(\frac{-B'}{\alpha^2}\right)+\left(\frac{A'}{(1-\alpha)^2}\right)\right] - \frac{A''}{[1+(A''-1)\alpha]^2} = 0 \tag{30}$$

The Eq. (30) is a polynomial of order five in terms of α and is calculated numerically.

3.3. AoI using TDMA scheme

In this scheme, the time slot n is divided into two separated time intervals so that the CN transmits its data in duration of τ_c and sensor m transmits its data during $1-\tau_c$ (as Fig. 3) both with the same power constraint. Since, the data transmission by CN and sensor m is occurred during one time slot and the fusion center updates its status if both transmissions are successful, hence, the age of information increases by one if at least one of the transmissions fails. The constraints on successful transmission can be considered as

$$R_{CN} > R_C \Rightarrow \tau_c \log_2(1+\gamma_{n,C}) > R_C$$
$$R_m > R_0 \Rightarrow (1-\tau_c)\log_2(1+\gamma_{n,m}) > R_0 \tag{31}$$

Like the discussions in Section 3.1, choosing the proper sensor among k sensors from M sensors is as the same as NOMA system. Besides, in each durations, there is no interference between CN and sensor m with assumption that $P_C = P_m = \frac{1}{2}P_T$. Therefore, the probability of successful transmission can be calculated as follows

$$\begin{aligned} P^{(D_C,D_m)}_{suc,TDMA}(n,m) &= Pr\{\tau_c \log_2(1+\frac{P_T g_{n,C}}{2\sigma_n^2}) > R_C\} \\ &\times Pr\left\{(1-\tau_c)\log_2\left(1+\frac{P_T g_{n,m}}{2\sigma_n^2}\right) > R_0\right\} \\ &\times \rho_C Pr\{m\} \\ &= (e^{-\frac{2C\lambda_{g,C}\sigma_n^2}{P_T}})(e^{-\frac{2D\lambda_{g,m}\sigma_n^2}{P_T}})\rho_C Pr\{m\} \end{aligned} \tag{32}$$

where $C = 2^{\frac{R_C}{\tau_c}} - 1$ and $D = 2^{\frac{R_0}{(1-\tau_c)}} - 1$. Thus, the average age of information for TDMA-based system is

$$AoI_{TDMA} = \frac{1}{M}\sum_{m=1}^{M}\frac{1}{P^{(D_C,D_m)}_{suc,TDMA}(n,m)} \tag{33}$$

3.4. AoI optimization problem for TDMA scheme

Now, we want to minimize the age of information for whole network under time schedule parameter in TDMA scheme. The *AoI* formula shows that to minimize the age for the network, we have to maximize the probability of successful transmissions, P_{suc} which is independent for different sensors. Then, the optimization problem can be considered as follows

$$\begin{aligned} \min_{\tau_c} AoI_{TDMA} &\equiv \max_{\tau_c}\{P^{(D_C,D_m)}_{suc,TDMA}(n,m)\} \\ &\equiv \max_{\tau_c}\left(e^{-\frac{2(2^{\frac{R_C}{\tau_c}}-1)\lambda_{g,C}\sigma_n^2}{P_T} - \frac{2(2^{\frac{R_0}{(1-\tau_c)}}-1)\lambda_{g,m}\sigma_n^2}{P_T}}\right) \\ &\equiv \min_{\tau_c}\{(2^{\frac{R_C}{\tau_c}}-1)\lambda_{g,C} + (2^{\frac{R_0}{(1-\tau_c)}}-1)\lambda_{g,m}\} \\ &s.t \quad 0 < \tau_c < 1 \end{aligned} \tag{34}$$

The objective function in Eq. (34) is convex since its Hessian exists and it is positive [28]. Thus, the optimum time schedule parameter can be obtained from the first derivative of object function which yields

$$-\frac{R_C\lambda_{g,C}2^{\frac{R_C}{\tau_c}}}{\tau_c^2} + \frac{R_0\lambda_{g,m}2^{\frac{R_0}{(1-\tau_c)}}}{(1-\tau_c)^2} = 0 \tag{35}$$

The Eq. (35) is calculated numerically.

4. Numerical results

In this section, first, we obtain optimal α^* from Eq. (30) and optimal τ_c^* from Eq. (35) for each sensor in NOMA and TDMA schemes, respectively. We consider different distances from PB for CN and the sensors, randomly chosen between 5 to 10 m as $d_c = 5(m)$, $d_1 = 5.5(m)$, $d_2 = 6(m)$, $d_3 = 6.5(m)$, $d_4 = 7(m)$, $d_5 = 7.5(m)$, $d_6 = 8(m)$ and $d_7 = 8.5(m)$. Also, we consider different distances form FC for CH and the sensors, randomly chosen between 30 to 40 m as $D_c = 30(m)$, $D_1 = 32(m)$, $D_2 = 33(m)$, $D_3 = 35(m)$, $D_4 = 37(m)$, $D_5 = 38(m)$, $D_6 = 40(m)$ and $D_7 = 40(m)$. The rest of the parameters are as following: $\eta_C = 0.95$, $\eta_m = 0.7$, $\sigma_n^2 = -60(dBm)$, $\gamma_0 = -40(dBm)$, $P_T = -40(dBm)$, $R_0 = 0.05$ (bit per channel use) and $R_c = 0.1$ (bit per channel use).

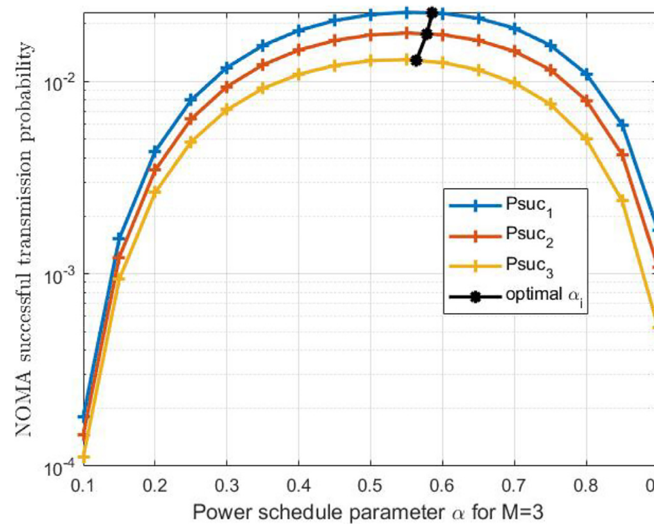

Fig. 4. $P^{(D_C,D_m)}_{suc,NOMA}(n,m)$ vs α.

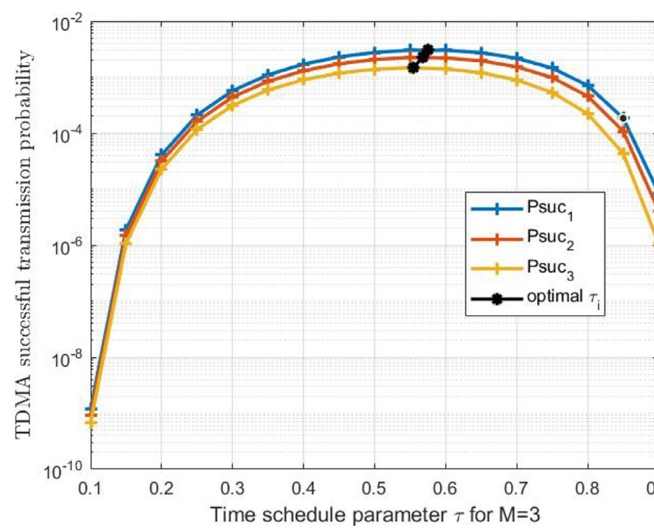

Fig. 5. $P^{(D_C,D_m)}_{suc,TDMA}(n,m)$ vs τ_c.

Fig. 4 shows the probability of successful transmission vs. α in NOMA scheme. The optimal α^* calculated numerically, is shown in the figure for three different sensors. As seen, $P^{(D_C,D_m)}_{suc,NOMA}(n,m)$ increases by decreasing the distance between the sensor and FC. As well, Fig. 5 depicts the probability of successful transmission vs. τ_c in TDMA scheme. The optimal τ_c^* calculated numerically, is depicted in the figure for three different sensors. It is seen that $P^{(D_C,D_m)}_{suc,TDMA}(n,m)$ also increases by decreasing the distance between the sensor and FC.

Now, we use α^* and τ_c^* obtained from numerical calculations to demonstrate AoI vs. different parameters. Figs. 6 and 7 shows AoI_{NOMA} and AoI_{TDMA} vs. PBs transmission power, P_E, for different amounts of α and τ_c, respectively. As expected, both diagrams confirm that age of information is minimum for optimal α and τ_c compared to the random and deterministic one.

In Figs. 8 and 9, the age of information in NOMA and TDMA schemes are shown vs. P_E for $\eta_C = 0.95$ and different amounts of η_m considering optimal values of α^* and τ_c^*. The more energy the amount of harvested, the less the age of information is obtained. However, the effect of η_m becomes worthless for larger P_E; i.e.

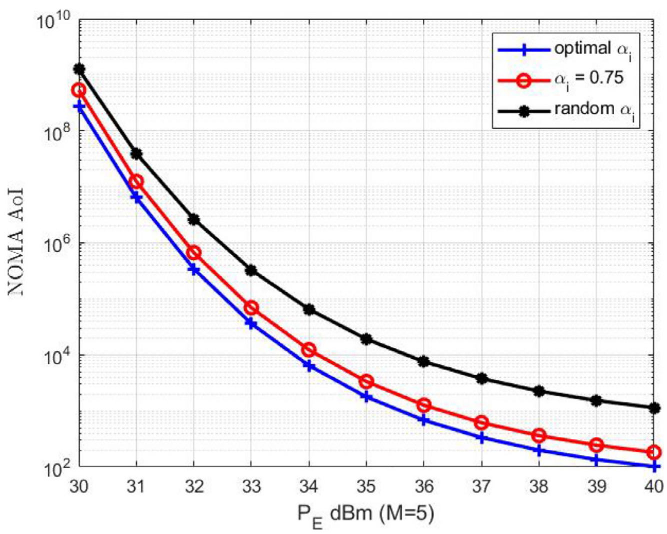

Fig. 6. AoI_{NOMA} vs. P_E for different α.

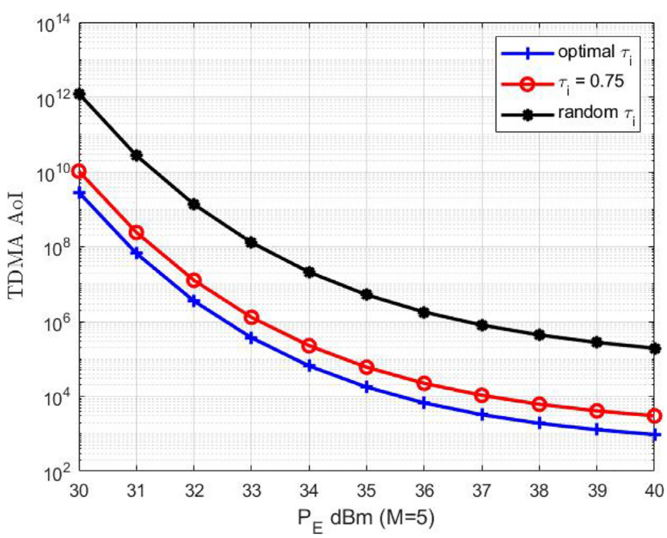

Fig. 7. AoI_{TDMA} vs. P_E for different τ.

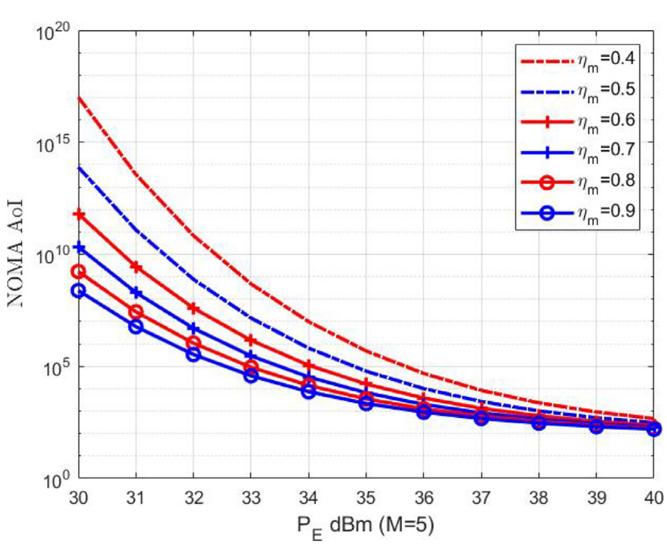

Fig. 8. AoI_{NOMA} vs. P_E for different η_m.

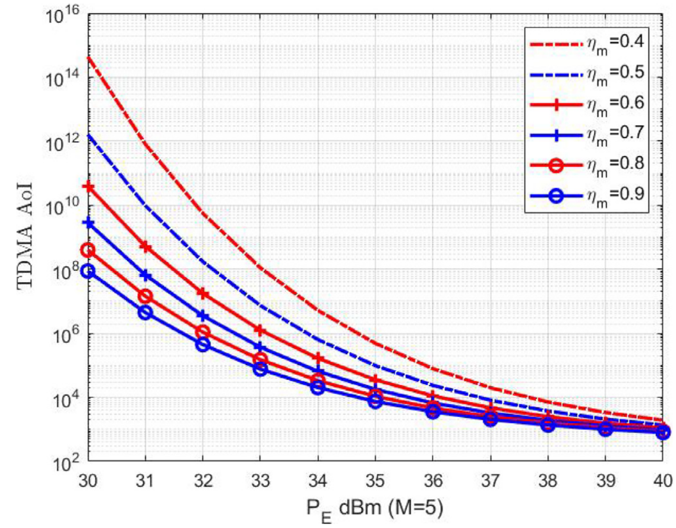

Fig. 9. AoI_{TDMA} vs. P_E for different η_m.

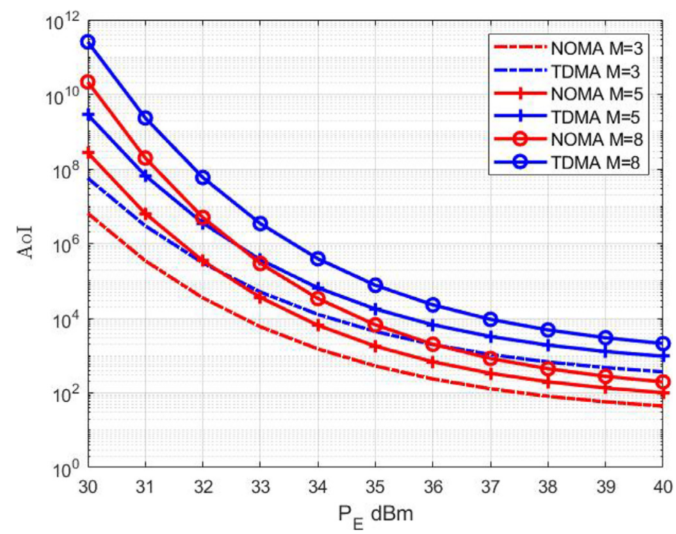

Fig. 10. AoI_{NOMA} and AoI_{TDMA} vs. P_E.

increasing the PBs transmission power can reciprocate the use of sensors with greater power absorption which would be cost effective when the number of sensors becomes large.

An important result emerges from the comparison of age of information between NOMA and TDMA schemes for optimal values of α^* and τ_C^*. Fig. 10. Depicts the age of information vs. P_E for different numbers of sensors around CN. As the number of sensors increases, AoI is increased for both schemes; But for a given M, AoI for NOMA scheme shows better performance compared to TDMA scheme.

5. Conclusion

In this paper, we have studied the age of information in the proposed system model for IoT sensor networks where fresh data can improve the performance of the system. We have derived closed form expressions for age of information using NOMA and TDMA schemes. We have obtained the optimal values of power and time schedule parameter through an optimization problem for both schemes. Applying the optimal points for scheduling parameters, minimum AoI is achieved under the mentioned conditions. Numerical results show the performance of AoI vs. the power transmission from a wireless energy transmitter for various parameters. It can be seen that NOMA shows better performance compared to TDMA scheme.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Hosein Azarhava received his B.Sc. and M.Sc. from university of Tabriz, Tabriz, Iran. Currently, he is pursuing the Ph.D. degree with University of Tabriz, and is a member of Wireless Laboratory (WiLab) of Faculty of Electrical and Computer Engineering in University of Tabriz. His research interests include digital communications, wireless communication networks, and wireless sensor networks.

Mehran Pourmohammad Abdollahi received his B.Sc. and M.Sc. from university of Tabriz, Tabriz, Iran. Currently, he is pursuing the Ph.D. degree with University of Tabriz, and is a member of Wireless Laboratory (WiLab) of Faculty of Electrical and Computer Engineering in University of Tabriz. His research interests include digital communications, wireless communication networks, and cognitive radio networks.

Javad Musevi Niya was born in Ahar, Iran. He received his B.Sc. degree from the University of Tehran and his M.Sc. and Ph.D. Degrees both in telecommunication engineering from Sharif University of Technology (SUT) and the University of Tabriz, respectively. Since September 2006, he has been with the Faculty of Electrical and Computer Engineering of the University of Tabriz, where he is currently an Associate Professor. His current research interests include wireless communication systems, wireless sensor networks, multimedia networks and signal processing for communication systems and networks.