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A directional multicasting-based architecture for wireless sensor networks

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ABSTRACT
Energy scarcity, limited transmission range and interference are the primary challenges that need to be considered judiciously for Wireless Sensor Networks (WSNs). Directional data transmission can improve the network capacity as well as the network lifetime by facilitating spatial multiplexing and range extension, which inherently yields interference reduction, as the result of concurrent data transmissions. Another promising method of achieving energy conservation is the transmission power control. Transmission power control also contributes to the mitigation of interference thereby promotes throughput by means of rendering multiple hosts to communicate in the same directionality simultaneously without impairing each other's transmissions. Harnessing the antenna directionality with dynamic power control gives the opportunity to WSNs to consume their scarce energy resources in a more efficient manner. In this article, we propose an energy efficient multi-cast routing-based architecture (MRBA). This architecture mainly bases on the idea of multi-cast routing methodology with hop-by-hop data fragmentation and power-controlled directional transmission. Multiple next-hop utilization during packet transmission together with directional relaying of the sub-packets provide interference reduction together with fair data transfer load sharing among the nodes. Simulation results show that significant improvements can be achieved in terms of energy saving and end-to-end delay enhancement with respect to omnidirectional architectures.

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Directional antenna; wireless sensor networks; energy conservation; directed beam

1. Introduction

Technological improvements have fortunately rendered computerized systems to perform life-threatening and time-consuming jobs for humankind in shorter durations (Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002). WSNs have gained great popularity due to their broad range application opportunities in the fields such as health, agriculture, military, surveillance, etc. (Ameen, Islam, & Kwak, 2010; Ghaffarzadeh & Doustmohammadi, 2014; Li et al., 2015). Especially, developments in micro-electro-mechanical systems (MEMs), signal processing and communication protocols have enabled the deployment of WSNs with satisfying costs in a broad range of application

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areas. Furthermore, easy deployment and self-setup facilities are the other major factors that have supported the fast proliferation of WSNs.

A WSN consists of self-configured and operating sensor nodes (Raposo, Rodrigues, Sa´ Silva, & Boavida, 2017) that are tiny-sized with limited communication range and lifetime duration. Thus, the energy conservation together with extended coverage is of paramount importance for WSN applications (Lee, Park, Oh, & Kim, 2014). Most of the research activities proposed thus far have focused on developing protocols, methodologies and architectures to prolong the lifetime of those limited-energy-supplied sensor nodes. A sensor node is mainly comprised of three entities: data gathering, processing and communication sub-units. The communication sub-unit is the prominent energy-consuming component of a sensor node. The amount of energy consumed during the transmission of a single bit is identical with the energy consumed during the transaction of 10,000 bits in the processing sub-unit (Dardari, Conti, Buratti, & Verdone, 2007).

Sensor nodes are manufactured in very small sizes to achieve low-cost operation and minimal maintenance (Cevik, Zaim, & Yiltas, 2012; Incel, 2011). Even thousands of sensor nodes may have to be deployed to a geographical area which can be dangerous for a human to gather data due to the type of the application. Especially for such hazardous situations and environments, replacing an energy depleted sensor node with a new one is not preferred (Mittal, Singh, & Sohi, 2017). Thus, traditional methodologies and constraints that are considered for ordinary wireless networks have become of secondary importance during the method development process for WSNs.

Omni-directional antennas propagate signals to every direction with equal energies in theory. Only a small fraction of the generated energy is retrieved by the intended receiver. The rest of the radiated energy travel in an unattended manner and disturb other sensor nodes that are irrelevant to the communication taking place. Thus, in order to prevent a possible collision, none of the other sensor nodes deployed in the omnidirectional vicinity is allowed to data transmission which highly decreases the overall throughput of the network (Atmaca, Ceken, & Erturk, 2008; Sabyasachi, Hu, Peroulis, & Li, 2006; Sundaresan, Ramachandran, & Rangarajan, 2009). In contrast, directional antennas can focus the radiated energy through a predetermined direction with a possible desired beam-width. Signals focused and propagated with a narrower beam-width can travel longer distances and arrive at the destination with the desired Signal-to -noise (SNR) ratios. Longer transmission range facilitates to decrease the number of hops on the route towards the destination which ultimately alleviates the latency. Furthermore, more concurrent transmissions are rendered to take place by occupying less spatial area by the signals. A higher number of simultaneous transmissions in a neighborhood inherently enhances the capacity and overall network throughput. Lastly, since the antenna gains of directional antennas are higher, the lower power level is sufficient to propagate the signals to the same range with respect to an omnidirectional antenna (Alam and Kim, 2016; Niu, Zhang, Cai, & Yuan, 2015; Ren, Zhang, & Li, 2017; Temel & Bekmezci, 2015; Zhang et al., 2012).

In this paper, we present a complete architecture that mainly considers the network lifetime maximization for WSNs. As is known and also mentioned previously, network lifetime is of great significance for researchers and developers. Thus, in our study it is intended as much as possible of nodes to share the burden of the data relay process which is also called in the literature as load balancing. Load balancing is a non-trivial methodology that cannot be ignored for lifetime maximization of the sensor nodes (Kacimi, Dhaou, & Beylot, 2013). A multi-cast routing-based methodology is utilized rather than a single candidate hop selection for the intermediate relay process. That is, an aggregated frame is multi-casted to a group of nodes to relay in which the header also includes the list of the relay nodes and their corresponding portion of the aggregated frame they are in charge with. The relay nodes fragment the incoming super-frame and re-multi-cast their share to their subsequent candidate relay-hops and the process goes on. Once the candidate nodes are selected according to their availability, the super-frame is multi-casted through the appropriate beams by using the directional multi-beam antenna model. Besides, the packets are transmitted through each beam with different power levels in order not to consume non-redundant energy and cause possible interferences for the other concurrent transmissions that take place in the same spatial region. As is known, the dynamic power utilization can achieve great energy savings which are especially crucial for WSNs (Berberoglu & Cevik, 2016). Simulation results clarify that the load balancing by means of opportunistic routing with multi-beam directional antennas provides significant enhancements in terms of end-to-end delay and energy savings.

The rest of the paper is organized as follows. Section 2 introduces some preliminary information about antenna types, power control and multi-cast routing. Section 3 clarifies the models and architecture developed in this study. Section 4 presents the simulation results and discussions among them. Lastly, Section 5 concludes the paper.

2. Preliminaries

This section clarifies some fundamental points which are crucial to cover the proposed architecture. Firstly, summarized information about directional antennas is given which is followed by the power control transmission issues and benefits in wireless communication. Multi-cast routing which is exploited for the purpose of sharing the burden of relay process among multiple nodes to maximize the network lifetime is introduced in the last part of the section. Throughout this study, it is assumed that all nodes are capable of performing fundamental functions such as transmit, receive and process data. However, major focus is directed towards the transmission and reception of data packets as the goal of the study is to compare the performance of directional radio antenna to omni-directional antenna.

2.1. Antenna model

There are almost twenty types of antennas in the literature that can be classified in different ways. However, especially for wireless communication, antennas are generalized as: omnidirectional and directional (Kraus & Marhefka, 2002; Yi, Pei, & Kalyanaraman, 2003).

2.1.1. Omni-directional antenna

Omni-directional also called isotropic antennas radiate and receive signals in every direction at equal energy levels. Propagating signals in undefined direction manner causes just a small fraction of the original radiated energy to be caught by the receiver (Korakis, Jakllari, & Tassiulas, 2008). The energy is unnecessarily consumed owing to this untargeted signal propagation which ultimately results with a shortage in coverage range. The inverse-square law states that a physical intensity is inversely proportional to the distance of the source of that intensity. When a point source radiates energy in three-dimensional space at equal energy levels in all directions, as the signals travel spherically further from the source, the intensity will spread out over a larger area. The area of the sphere that the original intensity spread overextends because of the reason that, the distance from the source indeed is the radius of the sphere. Thus, the original intensity level gets weaker by going further from the source. Three models have been mostly referenced in the literature to identify the predicted power level at the receiver: free-space, two-ray ground reflection and shadowing model. When the transmitter and receiver are apart from each other less than the crossover distance (d_c) that is clarified in Equation (1), free-space model (Equation (2)) better predicts the received power since at this proximity there is a single nearly-clear line-of-sight path between the communicating pair (Dang, Hong, Lee, & Lee, 2012; Friis, 1946; Gajurel, Malakooti, & Wang, 2007; Hekmat & Van Mieghem, 2004; Prasad, 1998; Rappaport, 1996; Zhu, Guo, Yang, & Conner, 2004).

$$d_c = 4\pi h_t h_r / \lambda \tag{1}$$

where h_t, h_r is the heights of the transmitter and receiver antennas respectively. λ is the wavelength in meters.

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 L} \tag{2}$$

The two-way ground reflection model also considers the ground-reflection path as well as the line-of-sight path between the communicating pairs. This model (Equation (3)) is utilized when the transmitter and receiver are apart from each other further than the crossover distance ($d > d_c$).

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^{\alpha} L} \tag{3}$$

where $P_r(d)$is the signal power at the receiver, P_t denotes the transmitter power, G_t and G_r express the antenna gains respectively. λ and L are the wavelength and system loss in meters respectively. α is the path loss exponent ranging from 2 to 6 depending on the pattern and environment that the communication takes place. A list of well-accepted values for different types of environments is given in Table 1.

Contrary to the former two models, the shadowing model considers the effects such as multi-path and fading which induce randomness to the received power level at the receiver (Gajurel et al., 2007).

Table 1. Values of the path loss exponent α for different environments.

Environment	α
Free space	2
Urban area	2.7–3.5
Shadowed urban area	3–5
Indoor	4–6

2.1.2. Directional (smart) antenna

Directional antennas facilitate using very narrow portions spatially of the common transmission medium-air by the nodes that yield simultaneous transmissions to take place which would possibly collide if omnidirectionally carried out. This is achieved by directing the main beam with the increased gain to the desired direction that covers the intended user(s) while utilizing nulls towards other directions to prevent possible collisions (Alpesh & Patrick, 2001; Atmaca et al., 2008; Atmaca, Çeken, & Erturk, 2009; Chryssomallis, 2000). Facilitating simultaneous transmissions inherently increases the system capacity and ultimate throughput. Moreover, shrinking the beam-width increases the antenna gain that renders relaying the signals to the same range with lower levels or transmitting to further distance with the same power level. Obviously, reduction in power usage maximizes the network lifetime which is the major concern for WSNs (Arora & Krunz, 2007; Atmaca, Ceken, & Erturk, 2007; Park, Park, Song, & Pack, 2013; Ramanathan, Redi, Santivanes, Wiggins, & Polit, 2005).

Smart antennas are the most popular and in-use directional antenna type that consists of array antennas. The configuration of arrays of antennas in a proper way yields significant spectrum and capacity enhancements. These antenna arrays are produced by settling the antennas in various geometrical combinations such as planar, circular, etc. The antenna array is not smart alone itself. The system becomes smart by connecting the antenna array to a Digital Signal Processor (DSP) and supporting with appropriate algorithms to adapt to the signal environment (Balanis, 2005; Kang, Poovendran, & Ladner, 2003; Saunders, 1999).

Smart antennas are generally categorized as:

Switched-beam antenna systems: Encompass a DSP-controlled switching system that enables to select and switch one of the predefined beams for transmitting or receive operations. The beam is selected so as to provide the highest gain for the area that covers the desired user. The sender and receiver must agree on the desired direction and corresponding beams for communication to dwell on the same link at the same time. After the handshaking process, the receiver switches to the agreed beam-antenna-element and focuses only on the signals that will arrive in that direction. Thus, any other signals that would ordinarily interfere will not affect the ongoing communication unless they use the same direction. General representation of a switched-beam antenna system is given in Figure 1 (Nicolaescu & Stoica, 2010; Winters, 2006).

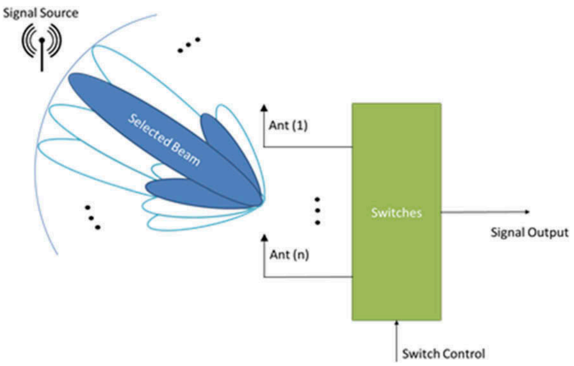


Figure 1. Switched-beam directional antenna.

Switched-beam smart antennas are also divided into two groups as single-beam and multi-beam systems. In single-beam systems (Figure 2(a)), signal propagation is handled through single beam due to the presence of single transceiver. In contrast, it is possible to transmit the same data through multiple beams at different directions by utilizing multiple transceivers as in multi-beam systems that enhance the diversity by means of spatial multiplexing (Figure 2(b)) (Atmaca et al., 2007; Lehne & Pettersen, 1999).

Adaptive-array antenna systems: In contrast to the pre-defined beam directions, the mobile user is tracked continuously in adaptive-array systems (Figure 3), and the main lobe is directed towards the intended user location with generated nulls at other directions to prevent possible collisions (Atmaca et al., 2007; Samhan, Shubair, & Al-Qutayri, 2006).

2.2. Power control

The limited capacity and energy scarcity are the primary drawbacks of WSNs. Methods are being considered to improve the spatial reuse and energy conservation for the sake of capacity and energy prudence. Power control is one of the choices offered for this purpose. Power saving can be achieved in two ways:

- Changing the states of the devices to low-power mode during the idle periods which 802.11 Power Saving Management (PSM) is based on. Research studies to date have revealed that the highest energy consumption is attributed to the data communication unit (Ebert, Stremmel, Wiederhold, & Wolisz, 2000; Feeney & Nilsson, 2001; Gobriel, Melhem, & Mossé, 2006). However, if the hosts stay in the idle state longer time when compared with the data transmission period, it is not the best way purely striving to save power by transmission power control (Gobriel

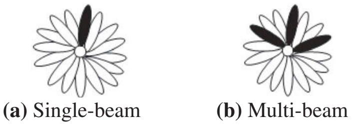

(a) Single-beam **(b)** Multi-beam

Figure 2. (a) Single-beam (b) multi-beam.

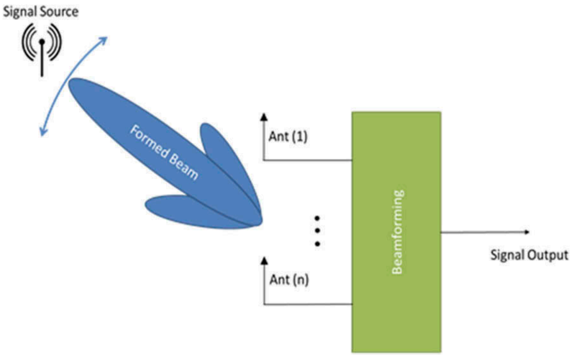


Figure 3. Adaptive-array directional antenna.

et al., 2006). It is identified that a significant amount of energy is consumed by the devices at idle states even though they do not make any transmission (Zheng, Hou, & Sha, 2007). Therefore, it is deduced that it is better for devices to change their states to a passive position at which they require minimum energy rather than holding at a constant level (Zheng, R., Hou, J. C., & Sha, L.).

- Original IEEE 802.11 applies constant power level during transmissions that is one of the primary prohibitive factors for the spatial reuse. Beyond the exposed terminal problem, it is sometimes possible for two transmissions to take place simultaneously without distorting each other by means of power control despite the RTS/CTS mechanism as illustrated in Figure 4.

As depicted in Figure 4, a concurrent transmission can also take place between C-D during a transmission between nodes A-B if node C can arrange its transmission power to the level that signals arriving at node B would not collide with the ones generated by node A.

The same is also true for directional antenna-utilized scenarios as presented in Figure 5. Assume that node A and B intended to transmit their packets to node C and D respectively. Signals emerge from node A destined for node C will interfere at node D with the signals emerge from node B if a standard power level applied through the network which is an obvious collision situation (Figure 5(a)). Moreover, energy is redundantly consumed though it is possible to convey the signals with consuming less effort. In contrast, it is possible for two communications to take place simultaneously by applying dynamic power utilization. If node A arranges its transmit power level according to the distance to node C, signals will not arrive at node D and cause a collision as shown in Figure 5(b).

2.3. Multi-cast routing

Energy concern is one of the major factors during the development process of routing algorithms for the scarce energy resource provisioned WSNs. Collisions and retransmissions

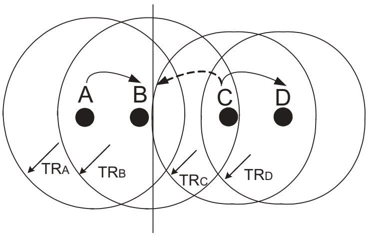
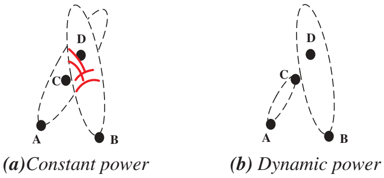


Figure 4. An illustration of the power controlled data transmission for the omnidirectional case.



(a)Constant power (b) Dynamic power

Figure 5. Transmission power patterns.

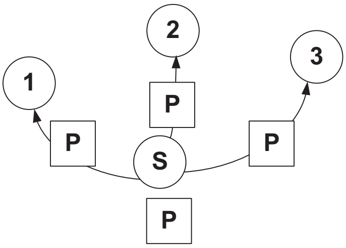


Figure 6. Multi-cast routing.

as a result of these collisions ultimately conclude with redundant energy consumptions. However, considerable energy savings can be achieved as well as enhancement in frame reduction if the packets are forwarded towards the paths that are maximally disjoint (Wieselthier, Nguyen, & Epfremides, 2002). Besides the collision factor, sharing the burden of relay process among the maximal number of nodes also yields great energy savings. Multi-cast routing (Figure 6) is one of the ways to achieve load sharing. Utilizing directional antennas during multi-cast-based routing renders to select multiple desired next-hops rather than disturbing all of them. Many studies have been performed about multi-cast routing strategies with directional antennas in the literature (Hou, Shi, Sherali, & Wieselthier, 2007; Wieselthier et al., 2002; Wieselthier, Nguyen, & Ephremides, 2002). Although multi-cast routing is employed up to now is for relaying the same data to multiple distinct receivers and also enhancing diversity multiplexing, in our architecture, we apply it for sharing the burden of relay process to achieve the lifetime maximization.

As illustrated in Figure 6, the packet (P) is transmitted to all receivers (1, 2, 3) in contrast to the unicast transmission at which there is a single intended receiver.

3. MRBA

3.1. Antenna model

In MRBA, a dynamic-power controlled multi-beam smart antenna model is utilized. That is, same data can be propagated through multiple disjoint beams with different power levels as shown in Figure 7 which is called as adaptive-power multi-beam forming (Park et al., 2013; Sundaresan et al., 2009). Powers of the distinct beams are adjusted according to the intended receivers' positions as shown in the sample topology depicted in Figure 7. That is, source node N_1, applies different transmission power levels for the transmissions to the nodes N_2, N_3 and N_4.

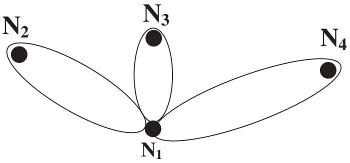


Figure 7. Adaptive-power multi-beam forming.

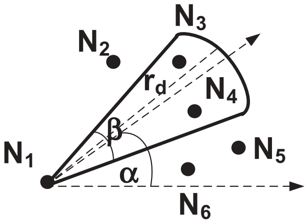


Figure 8. Directional coverage area for (α, β, r_d).

The directional coverage area of a beam is the transmission zone denoted by triple (α, β, r_d) in Figure 8 when Node 1 generates a transmission beam with an angle α, beam-width β and directional transmission range r_d (Ueda, Tanaka, Roy, Saha, & Bandyopadhyay, 2004):

However, at the set-up phase and during handshaking stage of data transmission, the antenna array generates main lobes in the form of switched-antenna beams. The antenna array is arranged to generate main lobes with constant power level during the set-up phase for the purpose of achieving maximal coverage range. By this way, the vicinity range expands and a higher number of nodes is notified.

3.2. Set-up phase

The set-up phase consists of two sub-phases as:

Node Deployment and Localization Phase: Nodes are assumed to be randomly deployed and aware of their positions with respect to the sink. This can be achieved by means of Global Positioning System (GPS) based hardware or some signal strength based localization techniques (Bhuvaneswari, Vaidehi, & Saranya, 2010; Moravek, Komosny, Simek, Girbau, & Lazaro, 2011).

Neighbor and Corresponding Direction Discovery Phase: As will be described in the following section, nodes are able to communicate in two modes as omnidirectional and directional. There are also challenges to be handled for directional-directional transmission (that is the mode both the transmitter and the receiver communicate in directional mode) such as deafness, hidden terminal problem, head of line blocking problem, etc. (Dang, Le, Kang, Hong, & Choe, 2015). Thus, nodes are assumed to wait at the receive mode omnidirectionally because of the lack of knowledge about the direction and beam desired by the transmitter.

At the discovery phase, each node broadcasts its position and identity information by using a contention-based MAC protocol such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) which IEEE 802.11 (Editors of IEEE, 1997) and 802.15.4 (IEEE Std. 802.15.4-2003, 2003) mainly based on Campolo, Molinaro, Casetti, and Chiasserini (2009) and Zhu, Li, and Liu (2014). Once a node captures the channel as a result of contention, it starts broadcasting by generating the main lobe in *Beam 1*direction and continues to sweep all the directions counter-clockwise till the starting point. The sweeping method (Korakis et al., 2008) is one of the prominent methods presented in the literature to mitigate the deafness problem. Since the nodes in the directional neighborhood of node1 are unaware of the desired beam direction that the broadcast will take place on, they should be informed by means of traveling every direction in a counter-clockwise manner. In the topology presented in Figure 9, N_1 is assumed to capture the channel and starts the broadcasting process on *Beam1* and continues with sweeping through all the beams. Nodes further apart than r_d (directional coverage range) will not get these broadcast signals such as N_6. Nodes N_2, N_3, N_4, and N_5, which are waiting in the omnidirectional mode, successfully receive the signals since their distances to N_1 is lower than r_d.

Nodes that are located in the coverage area of each beam detect the signals and record N_1's details such as ID, relative position and beam direction to be communicated to their DirectionalNeighborsDetails (DND) table.

It is clearly noticeable in Figure 9 that the broadcast notification signals arrive firstly to N_5 via *Beam 1*. The same information arrives also through *Beam2*. By this way, N_5 recognizes the possible directions that can be utilized to communicate with N_1. The cached direction information will be used by the nodes to communicate with each other without the need for re-discovery of the corresponding directions. Records generated in DND of N_5 for N_1 are given in Table 2:

where *TrBeam* and *RcvBeam* denote the beams that can be used for transmitting and receiving data to and from N_1 respectively. *X, Y, Busy, Time* express the *(X,Y)* coordinates with respect to the sink, busyness state and duration of the busyness respectively.

3.3. MAC

3.3.1. Collision avoidance

In the architecture proposed, Directional Virtual Carrier Sensing based collision avoidance protocol is utilized which is inspired from the previous studies proposed in the literature such as Directional Medium Access Control Protocol (DMAC) and Angular MAC (Choudhury, Yang, Ramanathan, & Vaidya, 2002; Sundaresan et al., 2009; Ulukan & Gürbüz, 2004, 2008). As is known, in the ordinary IEEE 802.11 MAC DCF protocol an

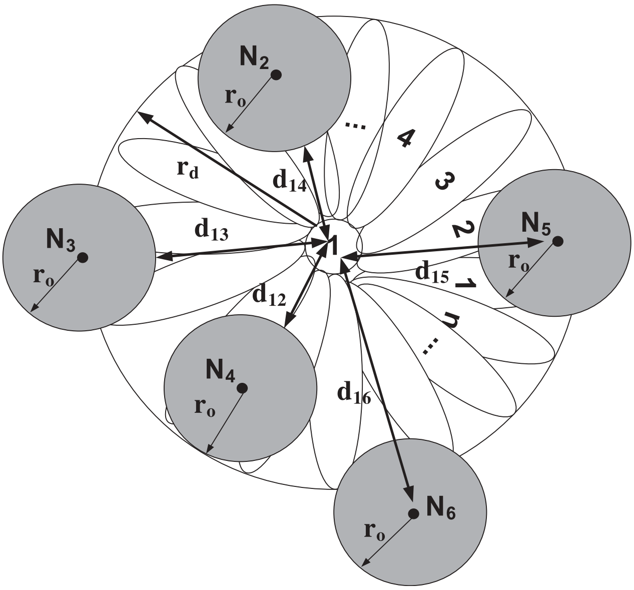


Figure 9. Sample topology.

Table 2. Records for N_1 in DND table of N_5 in Figure 9.

Ngh ID	TrBeam	RcvBeam	X	Y	Busy	Time
Node 1	10	1	X_1	Y_1	–	–
Node 1	9	2	X_1	Y_1	–	–

optional Request-to-Send (RTS)/Clear-to-Send (CTS) is present which is employed to mitigate the hidden and exposed terminal problems. During this handshaking and inherent neighbor notification process, a structure called Network Allocation Vector (NAV) is arranged by the neighboring nodes which identify the availability time of the communication medium. In DNAV of the neighboring nodes of the communicating pair, records are generated for each direction since there are multiple channels arising from multiple directions. A predefined reference direction is arranged usually towards 3 o'clock direction and other directions are determined by rounding counter-clockwise manner with beam-width intervals which are based on the idea of beam-switching. A similar approach is also employed in MRBA. The sender node starts sweeping operation as in the set-up phase after the arrival of the information from the network layer that defines the multi-next-relay hops. Details about the defined relay hop IDs are put in the packet and notified to all nodes in the maximal coverage range $r_d(\text{beamwidth}_{\min})$. Figure 10 shows the structure of a Directional RTS (DRTS) packet.

SID, $\text{NxtHop}_{1.n}$, $\text{TrBeam}_{1.n}$, $\text{RcvBeam}_{1.n}$ express the source ID, selected multi-next-relay hops, number of packets that NxtHopn will responsible for relaying (determined by the network layer), transmitting and receiving beam ids respectively. The selected relay hops reply back through the reverse direction of the incoming DRTS with a Directional CTS (DCTS) packet firstly. The sweeping operation is performed in a confined manner by selecting the appropriate directions in order to prevent redundant data transmission and energy consumption. The structure of a DCTS packet is presented in Figure 11.

where NxtHop_1 and RcvBeam_1 identify the id of the receiver and beam id that will be utilized by NxtHop_1 during receiving respectively.

As mentioned above, DCTS packets are not sent through all the directions as done for broadcast packets in the set-up phase. In contrast, they are propagated through the beam directions to the nodes that are available and reside on the next tier. Algorithm 1 identifies the DCTS receiver selection method that a next-hop *n* applies for the transmission of which the source is *s*. The nodes that are located further to the sink than node *n*, and non-neighbor of the source node *s* are added to the receiver list. By this way, any potential interferer neighbor will be warned to not to make attempt for selecting the occupied direction.

SID	NxtHop_1	NumOfPcks_1	TrBeam_1	RcvBeam_1	●●●	NxtHop_n	NumOfPcks_n	TrBeam_n	RcvBeam_n

Figure 10. DRTS packet structure.

SID	NxtHop_1	RcvBeam_1

Figure 11. DCTS packet structure.

Algorithm 1: DCTS receiver selection method

```
DCTSRcvSelection(){
  for (i←1 to sizeOf(n.Neighbors)) do
    if((n.Neighbors[i].distToSink > n.distToSink)
      &&(n.Neighbors[i].isNeighborOf(s)==false))
        n.DCTSRcvrList.add(Neighbors[i])
    end if
  end for
}
```

A sample event-based WSN application topology is depicted in Figure 12. Assume that N_1 is the source node and inherently the ultimate destination is the sink. Also, assume that N_5 is one of the multi-next-relay hops of N_1. N_5 does not need to pass DCTS packets to nodes N_9, N_{10}, N_{11}, N_{12}, N_{13} because these nodes are already deployed geographically closer to the sink and they would not attempt to forward their packets to a node that is farther away from the sink than themselves. Obviously, N_4 and N_2 can be the potential interferers for the ongoing transmission because they can select N_5 as the next hop if any transmission emerges from them. Eventually, DCTS packet is sent through nodes N_4 and N_2 only.

3.3.2. Frame generation

In our architecture, frame sizes are not constant. That is, initial frames generated by the source nodes that are located further positions are larger than the ones generated by the nodes that are closer to the sink. That is, the size of a frame generated by N_2 is not identical to the size of a frame generated by N_{15} in Figure 12. The frame size will be directly related to the tier number that the source node resides. Topology is partitioned into tiers. The width of each tier is calculated as $tierLength = Tr_d(beamwidth_\alpha)/2$, where $Te_d(beamwidth_\alpha)$ denotes the transmission range of a node with a beamwidth α. By this way, any two nodes that are vertically located at the furthest points of the two adjacent tiers can communicate. The number of packets that a frame generated at the source node is calculated as $frameSize = (tierNo)^F$. $tierNo$ is the tier number that the source node resides and calculated as $tierNo = \lceil topVrtL/tierLength \rceil$. F is a parametric factor and determined as 2 for the sake of simplicity during simulations.

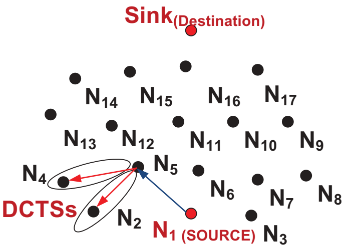


Figure 12. DCTS transmission scenario.

3.4. Multi-cast-based routing protocol

The multi-cast routing applied in our architecture based on generating a frame comprised of multiple packets and relaying the partitions of the incoming or original frame to the available next relay hops. Every next hop in the coverage range and on the 180° horizontal view that is not busy can be selected as next-relay hops. Any next relay-hop receiving the frame subsequently fragments the incoming frame into partitions and retrieves the partition that is identified by the sender in the DRTS packet and discards the rest. The number of packets that each subsequent relay retrieves which is identified in the DRTS packet is calculated as $NumOfPcks_n = min(TierNo_n, \; NumAvNxtHop)$, where $TierNo_n$, *NumAvNxtHop* denote the tier number of the relay-hop$_n$ resides and number of available next hops respectively. Sometimes it is possible that multiple available next-relay-hops are present. Taking the minimum of *TierNo* and *NumAvNxtHop* prevents the excessive number of fragmentations. If the number of packets in the frame is not multiple of the number of the available next-relay hops, then the nodes reside angularly closer to the sender-sink line are adjusted higher number of packets. In Figure 13, an exemplary fragmentation scenario is illustrated in which the source node is located in the fourth tier. A packet that is comprised of twenty-five-unit sub-data is generated at the source and transmitted to the desired receivers. At the next tier, one of the receivers detaches the first seven-unit sub-data and relays it to the available receivers resided at the following tier towards the sink and the process goes on.

The routing and frame fragmentation processes are better explained on the scenario presented in Figure 14:

In Figure 14, the packet quantity in the original frame is equally adjusted for the next-hops 1, 2 and 3 which is notified to these nodes by the DRTS packet during notification stage. The initial frame structure is given in Figure 15:

where SRCID and DID express the IDs of the source and the sink. In the scenario above, node S multi-casts nine packets to the next relay nodes 1, 2 and 3. At each hop, the incoming frame is partitioned if possible and multi-casted to the subsequent next hop candidates. Nodes 1, 2 and 3 divide the incoming packet into the amount of sub-units which is identified in the DRTS packet and each continue to relay the sub-units that are under their responsibility towards the destination. The total amount of energy consumption slightly increases; however, the maximum of the energies consumed by every single node individually significantly decreases even in this basic scenario as presented in Table 3:

where E_R and E_T are the energy quantities of the energy consumed by a node during packet reception and transmission respectively; G_d expresses the gain

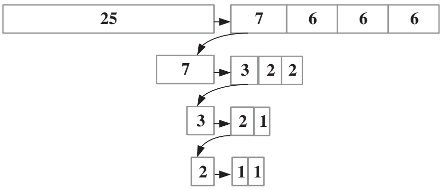


Figure 13. Sample fragmentation scenario.

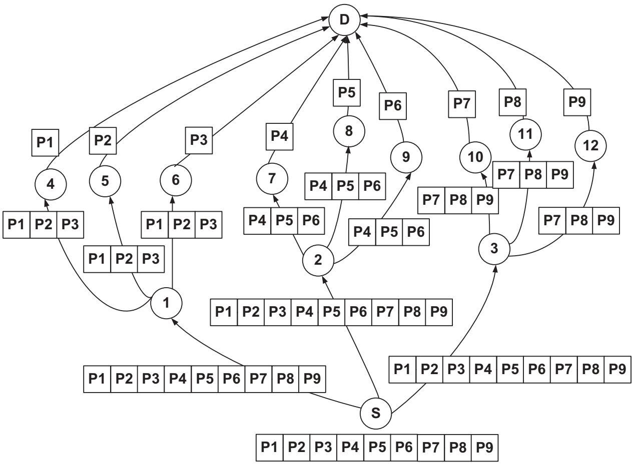
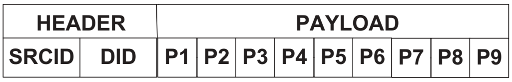


Figure 14. Sample multi-cast-based routing scenario.



HEADER		PAYLOAD								
SRCID	DID	P1	P2	P3	P4	P5	P6	P7	P8	P9

Figure 15. Frame structure.

Table 3. The amount of energy consumed by the nodes in the topology presented in Figure 14.

Node	Unicast	Multi-cast
1	–	$(9E_R+3E_T)/G_d$
2	$9E_R+9E_T$	$(9E_R+3E_T)/G_d$
3	–	$(9E_R+3E_T)/G_d$
4	–	$(3E_R+E_T)/G_d$
5	–	$(3E_R+E_T)/G_d$
6	–	$(3E_R+E_T)/G_d$
7	–	$(3E_R+E_T)/G_d$
8	$9E_R+9E_T$	$(3E_R+E_T)/G_d$
9	–	$(3E_R+E_T)/G_d$
10	–	$(3E_R+E_T)/G_d$
11	–	$(3E_R+E_T)/G_d$
12	–	$(3E_R+E_T)/G_d$

Table 4. Simulation parameters.

Radio transmission data rate	250 Kbps
d_0 (threshold distance)	50 m
R_0 (coverage radius)	100 m
E_{elec}	50 nJ/bit
εfs	10 pJ/bit/m^2
Emp	0.0013 pJ/bit/m^4
$E_{Residual\text{-}Initial}$	10 J

exploited by directionality. As is known, energy consumption during transmission process (E_T) is higher with respect to the consumed energy during the reception (E_R). As identified Table 3, the total amount of energy consumed in the topology by the unicast strategy is $18E_R+18E_T$ and the maximum individual energy consumption is performed by the nodes 2 and 8 which is $9E_R+9E_{T.}$ However, the total amount of energy consumed by the multi-cast strategy is $(54E_R+18E_T)/G_d$ and the maximum individual energy consumption is performed by the nodes 1, 2 and 3 which is $(9E_R+3E_T)/G_{d.}$ Obviously, packet relay burden is shared by multiple nodes and the ultimate lifetime maximization is achieved.

4. Evaluation

In this section, we evaluate the key performance metrics of the MRBA protocol via extensive simulations. The proposed approach is compared with 802.11-Omni Directional and the results are presented. Performance assessment is made in terms of energy consumption and delay. The metrics that are evaluated during simulations are given in the following:

- End-to-end delay: is the time that elapses between the time that the first packet emerges at the source and the time when the last packet arrives at the sink.

In order to evaluate delay in the system, the following general expression was used:

$$\text{Total Delay} = \sum_{j=1}^{F} \sum_{i=1}^{P} p_{(j,i)t}$$

Where:

F – is the total number of frames transmitted from the source to the sink throughout network lifetime.

P – is the total number of packets in a given frame.

$P_{(i,j)t}$ – is the time, *t*, taken for the *i*th packet of frame *j* to be transmitted from the source to the sink.

- Average Energy Consumed: the total energy consumed in the network by all sensor nodes. Since the transmission subunit consumes most energy, energy consumptions from other sub units, such as; the receptions subunit and the processing subunits are ignored in this study.
- Residual Energy: is the total remaining energy levels of the nodes in the network.

Major factors that affect these metrics are beam-width (beam angle) which stands for the directionality of the antenna and density of nodes that participate in the topology. The way how these factors affect the metrics described above is obtained as a result of detailed simulations.

Simulations are performed for 100 rounds on a 500 m * 500 m square network area. Events occur randomly in the network without depending on any constraint. A sink equipped with a single full-duplex transceiver is positioned at the top side of the topology (coordinates x = 250, y = 0). It is assumed that each sensor node is equipped with a single multi-beam transmission capable radio-unit with a transmission rate of 250 Kbps.

Following the values defined in the literature for the parameters expressed in Section 3, the values given in Table 1 are considered during energy consumption calculations. It should be noted that the purpose of this study is to compare the performance and success packet transmission of omni and directional antenna hence parameters such as the Received Signal Strength Indicator (RSSI), LQI are not discussed in this study. All sensors are considered to be identical with an initial residual energy of 10 J. The omnidirectional transmission range of each sensor node is set to 50 m. The energy consumed in transmitting a bit over 1m distance is taken as 10 pJ/bit/m^2 and the energy consumed in receiving a bit is set to 50 nJ/bit.

In the proposed approach, multi-cast routing is a crucial determinant of energy consumption. Therefore, the impact of the number of next hops for multi-cast routing on different performance metrics of the network is analyzed briefly. As the number of relay-next hops increases, multiple alternative routes emerge. Thus, these alternative routes can be followed to relay the packets from the originating node towards the sink. This methodology alleviates the burden of the nodes participated around the center vertical of the topology.

Obviously, the packet transmission load is shared among the nodes distributed as much as possible when multipoint broadcast routing is applied at each step, and the next hop count increases. Thus, since more nodes share the energy consumption burden, the network lifetime inherently prolongs as depicted in Figure 16. The number of multi-cast relay-next hops is defined constant at the beginning of the simulation. Although, the number of relay-next hops is defined constant formerly, this parameter is the targeted value that can be violated regarding the availability of the next hops and antenna beams. That is, if the number of available neighbors and corresponding beams is lower than the intended quantity, then the smaller one is assigned as

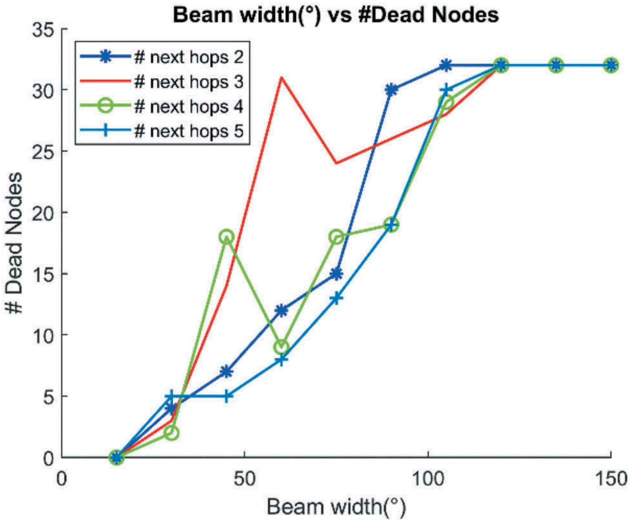


Figure 16. Impact of multi-cast routing on lifetime.

NumOfNextHops = min (NextHopsInt, NumAvNxtHop) where *NextHopsInt, NumAvNxtHop* represent the intended multi-cast relay-next hop quantity defined initially and available next hops respectively.

Another prominent factor determining the network performance is the directivity of the transmissions. As clearly seen in Equation (4), the antenna gain is strongly related to the directivity of the antenna (Balanis, 2005):

$$G(\theta,\ \varphi) = e_{cd} D(\theta,\ \varphi) \tag{4}$$

Directivity increase yields the signals to be transmitted further distances with the same power levels or less power to intended destinations. The impact of directivity increase on network lifetime is presented in Figure 17:

Figure 17 supports the idea expressed formerly, that is, network lifetime prolongs as the packet relay burden is shared among more nodes. This is because more energy is saved by directional sensors as opposed to omni-directional sensors as demonstrated in the figure because generally less irrelevant transmissions are performed, furthermore, the most optimal route is always calculated and chosen.

Another important parameter in communications is the delay. In this study, end-to-end delay refers to the time that elapses between the time that the first packet emerges at the source and the time when the last packet arrives at the sink. As the node density increases and more nodes are involved in packet transmission, the time to reach the base station inherently increases as well which is presented in Figure 18. Owing to the fact that node deployment was random for every given epoch, the delay is very dependent on the positioning of the nodes. It is due to this fact that there is no particular trend to the distribution of the delay values in this study.

Since increasing the beam-width will diminish directivity and cause wider areas to be corrupted during a particular transmission, another transmission to take place in that area needs to wait for its order, which inherently exacerbates delay. Impact of directivity on delay is presented in Figure 19.

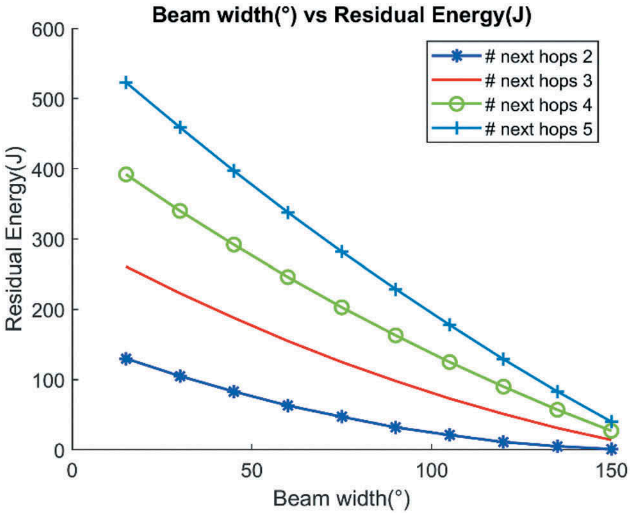


Figure 17. Impact directivity on lifetime.

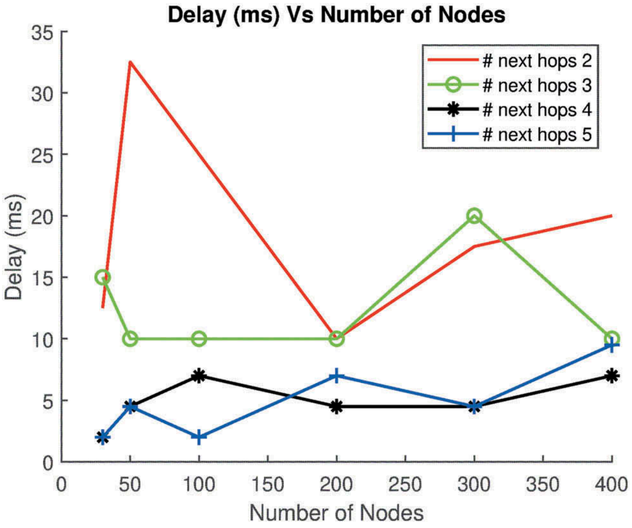


Figure 18. Impact of node density on delay.

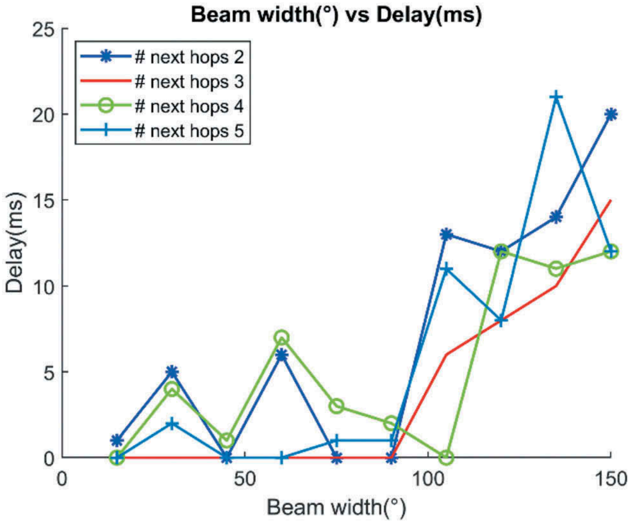


Figure 19. Impact of directivity on delay.

Lastly, directional vs omnidirectional comparison in Figure 20 provides a better insight into how directional antennas defeat omnidirectional antennas and provide substantial benefits. An omni-directional antenna consumes four times more energy than using directional antenna on average.

5. Conclusion

In this study, we propose a new multi-cast routing-based architecture called MRBA that exploits directional antennas to alleviate the crucial problem of WSNs, that is, energy

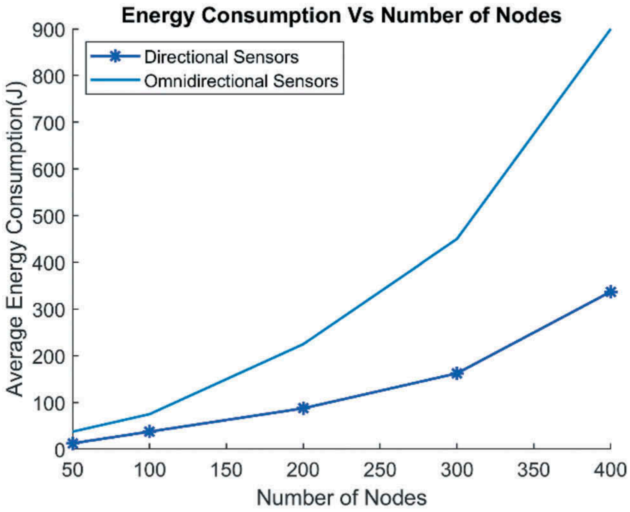


Figure 20. Directional antenna vs omnidirectional antenna comparison.

consumption. Enhancing the directivity of antennas yield longer transmission distances that ultimately results in less power consumption to relay packets to the intended destinations. Narrowing the beams increases the directivity, which inherently provides less area to be corrupted. Besides, multi-casting the packets at each step exploits spatial multiplexing provided by multi-beam directional antennas. Results of the exhaustive simulations demonstrate that our approach provides significant gains in terms of network lifetime prolongation and delay. For future work, we intend to improve our approach to be applied to Wireless Multimedia Sensor Networks by including Quality of Service mechanism.

Disclosure statement

No potential conflict of interest was reported by the authors.

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