

establish multihop routing paths from network nodes towards the BS. In this paper we present how to implement relation-oriented cooperation within a neighborhood and based on locally taken decisions construct spatial communication path that fulfills globally defined criteria.

III. RELATED WORK

There are several routing algorithms for WSNs that allow sending information between nodes and the BS. So called flat algorithms (i.e. flooding) ensure that every information will finally reach the BS unless there is no node that can communicate to the BS directly [1], [3]. Such protocols use broadcast communication and simply flood the whole network with any information causing collisions in the communication channel and retransmissions. Apart from the waste of energy, flooding also decreases the bandwidth, lowers communication speed or simply cuts of some parts of the network. These drawbacks are minimized in gossip protocol [5] where the broadcast communication concerns only neighboring nodes. Such routing protocols as Data Centric Routing (DCT), Sensor Protocol for Information via Negotiation (SPIN) try to orient communication towards time, query, event (DCT) or information requirements (SPIN). Directed Diffusion protocol enables to minimize energy consumption during the routing protocol further but a lower efficiency (mainly due to large number of queries) is its drawback. Rumor Routing [1] is another attempt to take advantage of agents and directed communication. This gives good results for a limited number of situations when costs of additional agents are negligible comparing to the overall costs. Hierarchical protocols, such as LEACH, TEEN and PEGASIS [9], [13] aim at directed communication that is achieved through clustering or divisions into zones. This proposal use routing protocols based on tree or chain structures.

All aforementioned protocols construct a single multi-hop communication path between any node and the BS. Established communication path is utilized as long as it is energetically justified [6], [8]. If energy level of a node that belongs to the path, drops below specified level then communication path discovery algorithm is being run again. The whole process is then repeated until no path can be found.

IV. RELATIONS, CHAINS OF ACTIONS

Our approach utilizes three basic binary relations defined on the set of actions (Act) that describes communication activities in WSN. These three relations: collision (\varkappa), subordination (π) and tolerance (ϑ), were first introduced and described by Jaroń [7] and later by Nikodem et al. [11], [10]. Any binary relation \mathcal{R} on set A can be represented as a set of ordered pairs $\langle x, y \rangle$ where $x, y \in A$ and x, y are in relation \mathcal{R} (which we denote $x\mathcal{R}y$):

$$\mathcal{R} = \{ \langle x, y \rangle \mid x, y \in A, x\mathcal{R}y \}. \quad (1)$$

Thus one may treat relation as a set such that $\mathcal{R} \subset A \times A$. We may also define the converse of relation \mathcal{R} as:

$$\mathcal{R}^{-1} = \{ \langle x, y \rangle \mid x, y \in A, y\mathcal{R}x \}. \quad (2)$$

Based on these definitions we can describe basic properties of \varkappa, π and ϑ as follows [7]:

$$\pi \cup \vartheta \cup \varkappa \subset Act \times Act \neq \emptyset, \quad (3)$$

and

$$\iota \cup (\pi \circ \pi) \subset \pi, \quad (4)$$

where ι is a identity relation on the set Act . Formula (3) states that all three relations are binary on non-empty set of $Actions$. Formula (4) states that subordination is reflexive ($\iota \subset \pi$) and transitive ($\pi \circ \pi \subset \pi$). Further

$$\pi \cup \vartheta^{-1} \cup (\vartheta \circ \pi) \subset \vartheta \quad (5)$$

means that:

- subordination implies tolerance – if π holds for some $x, y \in Act$ then ϑ also holds for these,
- tolerance is symmetric – if $x\vartheta y \Rightarrow y\vartheta x$,
- subordinated action tolerates all actions tolerated by the dominant – if $(x\pi y \wedge y\vartheta z) \Rightarrow x\vartheta z$.

For collision relation we have that

$$\varkappa^{-1} \cup \{ \pi \circ \varkappa \} \subset \varkappa \subset \vartheta' \quad (6)$$

where ϑ' is the complement of ϑ :

$$\vartheta' = \{ \langle x, y \rangle \in X \times Y \mid \langle x, y \rangle \notin \vartheta \}. \quad (7)$$

Axiom (6) states that collision is symmetric, disjoint to tolerance and subordinated action must be in collision with action being in collision with dominant. Paper [10] presents how to use relations π, ϑ and \varkappa in order to model spatial communication. Subordination π is responsible for multihop path determination, tolerance ϑ allows multiple paths to exist simultaneously, while collision \varkappa forms restrictions for the communication space. This paper focuses on subordination

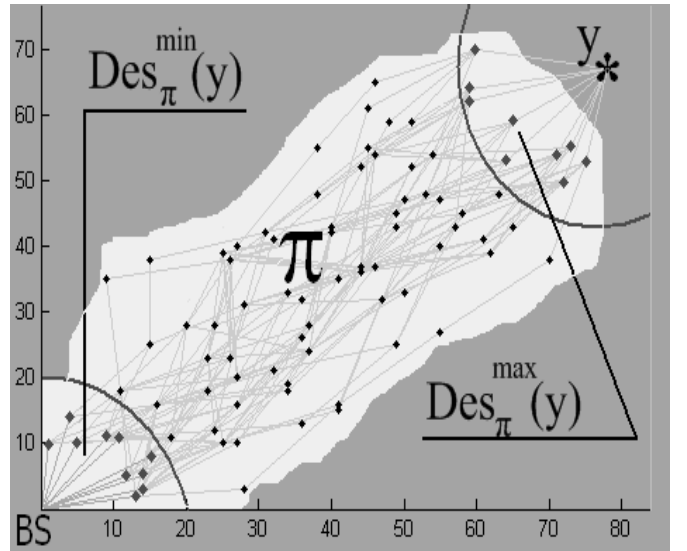


Fig. 1. $Des_{\pi}(y)$ area in WSN.

since among other two relations it is the most important for determination of a multihop communication path. It is also the only one relation that is transitive enabling to construct chains of WSN's nodes that will establish communication paths.

Because π is transitive we can define chain of subordination relation π^n :

$$\pi^n = \pi^{n-1} \circ \pi; \quad \dots \quad \pi^2 = \pi^1 \circ \pi; \quad \pi^1 = \pi. \quad (8)$$

Then

$$\pi^n = \{ \langle x, y \rangle \mid \langle x, y \rangle \in Act^{n-1} \times Act \} \quad (9)$$

where x is the nearest descender of y (or y is the nearest ascender of x).

Using composition of relation is more troublesome comparing to set of node y descenders:

$$Des_\pi(y) = \{x \in Act \mid (\exists n \in N)(x \pi^n y)\} \quad (10)$$

We can take many subsets of $Des_\pi(y)$ but only some of them will be useful in future investigations. Three of them are the most important ones:

$$Des_\pi^{min}(y) = \{x \in Des_\pi(y) \mid (BS \pi x)\} \quad (11)$$

$$Des_\pi^{mis}(y) = \{x \in Des_\pi(y) \mid \neg(\exists z \in Des_\pi)(z \pi x)\} \quad (12)$$

$$Des_\pi^{max}(y) = \{x \in Des_\pi(y) \mid (x \pi y)\} \quad (13)$$

The (11) is a set of the nearest ascenders of the base station while the (13) is a set of nearest descenders of y (fig.1). From remaining subsets of $Des_\pi(y)$ we will focus only on these that refer to multi-hop communication path between node y and the BS. We will denote these subsets as $Chn_\pi(y)$ and we will construct the subordination relation in order to maximize the cardinality of $Des_\pi^{min}(y)$ and $Chn_\pi(y)$.

To construct a proper subordination relation, well suited for WSN communication path modeling, we have to remember that according to eq. (4) relation π is transitive ($(\pi \cdot \pi) \subset \pi$) and reflexive ($\iota \subset \pi$). In case two nodes of the network are situated close to each other we usually assume that they "glue" together forming a single node of communication:

$$(\forall x, y \in Act)(x \pi y \wedge y \pi x \Rightarrow x = y), \quad (14)$$

which means that subordination becomes antisymmetric. Moreover, in WSN it is obvious that node does not send message to itself. Hence for modeling communication activity we refine subordination as irreflexive.

$$(\forall x \in Act)(\neg(x \pi x)). \quad (15)$$

Note that combination of transitivity and irreflexivity implies that if $x \pi y$ holds, then $\neg y \pi x - y$ is not subordinated to x . In this way we obtain a stronger asymmetric property comparing to (14)

$$(\forall x, y \in Act)(x \pi y \Rightarrow \neg(y \pi x)). \quad (16)$$

This property ensures that there are no loops in $Chn_\pi(y)$ chains and relation π is directed. According to the aforementioned requirements (transitivity, (16), (15)) for the relation π we get that subordination is a strict ordering relation on a set of actions $Des_\pi(y)$. Nevertheless, π does not partition the set $Des_\pi(y)$ but as a result we obtain linear ordered chains $Chn_\pi(y)$.

Due to limited communication range of a single node smaller than the size of the WSN, the relation π is never total. Generally, concerning relation π , intensity quotient within

multi-hop network is rather low. However, if we consider this quotient within node's neighborhood then the range of possible values is expanded.

V. COOPERATION WITHIN NEIGHBORHOODS

Cooperation is crucial activity in a multi-hop WSN [4], [14]. Most nodes do not communicate directly with the base station because it is out of node's radio communication range. WSN is really distributed, nodes provide necessary computations, communicate with each other within some neighborhood, and maintain state of the whole network.

There are many WSN algorithms which take advantage of some concept of a neighborhood (e.g. multi-hop, reliable, bi-directional or geographic). That is why we start from neighborhood definition. Let us define $Map(X, Y)$ as a set of mapping functions from X onto Y (surjection). Where $Sub(X)$ is defined as a family of all X subsets. We define the neighborhood \mathcal{N} as follows

$$\mathcal{N} \in Map(Nodes, Sub(Nodes)). \quad (17)$$

Thus, $\mathcal{N}(k)$ is the neighborhood of node k , and $\mathcal{N}(S)$ is the neighborhood of S (set of nodes) defined as:

$$\mathcal{N}(k)_{k \in Nodes} = \{y \in Nodes \mid y \mathcal{R}_{\mathcal{N}} k\}, \quad (18)$$

$$\mathcal{N}(S)_{S \subset Nodes} = \{y \in Nodes \mid (\exists x \in S)(y \mathcal{R}_{\mathcal{N}} x)\}. \quad (19)$$

Paper [12] analyses different definitions of locality that can be found in the literature. It also presents advantages and drawbacks of dividing network into clusters (clustering), single routing path and neighborhoods. Native locality has been pinpointed as the one, to work with neighborhood abstraction that is determined by native (mostly technical) constraints like radio link range. Whereas clustering is some kind of simplification, that facilitates computation and truncates the set of possible solutions at the same time. As the result, the native neighborhood was advised as the most suitable form of the local range. Considering native neighborhoods within WSN network they are indexed family of sets $\mathcal{N} = \{N_i \mid i \in I\}$ for which following properties hold:

$$(\forall i \in I)(N_i \neq \emptyset) \wedge \bigcup N_i = Nodes \quad (20)$$

$$(\forall i, j \in I \mid i \neq j)(N_i \cap N_j \neq \emptyset), \quad (21)$$

which relate to local (at any node) condition:

$$(\forall y \in Nodes)(\exists \sim i \in I \mid y \in \bigcap N_i \neq \emptyset), \quad (22)$$

formulated here a little stronger than (21) because $\exists \sim$ means exist as many as feasible". It means that native neighborhoods do not divide the set of WSN nodes into mutually exclusive subsets.

Having well defined one-hop (native) neighborhoods, let us decompose globally defined chains in $Des_\pi(y)$ for identical local task ascribed to each node. Once WSN is being created, during self-organizing process, distance between nodes and BS is being calculated - expressed by a number of necessary hops to reach the BS. The procedure begins with a broadcast message 'my status: 0-hops-to-BS' sent from BS. Every node

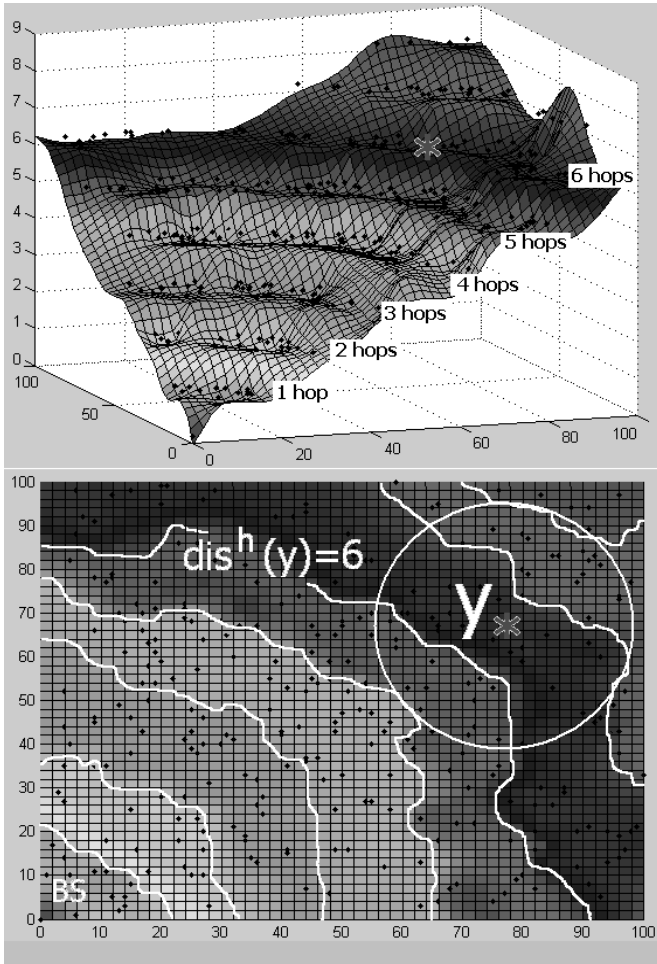


Fig. 2. Distance from BS(0,0) (measured in hops) and $\text{dis}^h()$ zones.

that will hear the 'my status: X-hops-to-BS' message for the first time sets its status to '(X+1)-hops-to-BS' and broadcasts the 'my status: (X+1)-hops-to-BS' message. When this procedure is finished every node with status X+1 can communicate with at least one node with status X. As a result any node k knows its hop distance from the BS ($\text{dis}^h(k)$) and distances of all of its neighbors ($\text{dis}^h(i)$ where $i \in N(k)$, fig.2). Based on this information it is possible to split neighborhood $N(k)$ into three sets:

$$\begin{aligned} N_{<}(k) &= \{y \in N(k) \mid \text{dis}^h(y) < \text{dis}^h(k)\} \\ N_{=}(k) &= \{y \in N(k), y \neq k \mid \text{dis}^h(y) = \text{dis}^h(k)\} \\ N_{>}(k) &= \{y \in N(k) \mid \text{dis}^h(y) > \text{dis}^h(k)\} \end{aligned} \quad (23)$$

which are mutually exclusive and collectively exhaustive $N(k)$ but they are not partition of a set $N(k)$, because of

$$(\exists k \in WSN)(N_{<}(k) = \emptyset \vee N_{>}(k) = \emptyset \vee N_{=}(k) = \emptyset). \quad (24)$$

Considering relation π , node's $k \in \text{Des}_\pi(y)$ communication activity within neighborhood becomes limited to:

$$N_\pi(k) = \{y \in N(k) \mid y\pi k\} \quad (25)$$

Knowledge of the set $N_{<}(k)$ (23) allows a node k to determine elements of the sets (25) in order to retain a data-flow direction

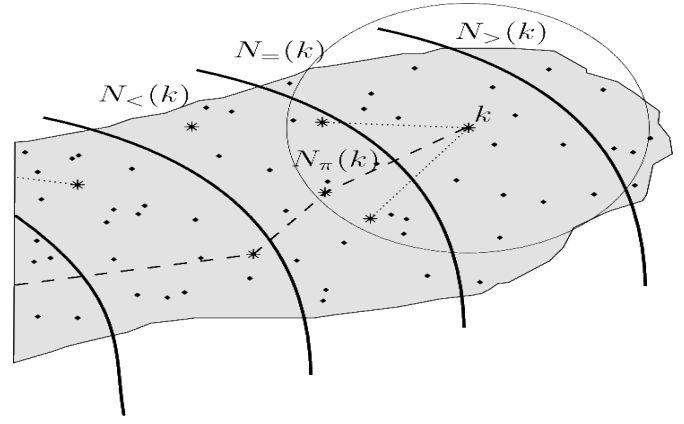


Fig. 3. Building $\text{Chn}(k)$ element within neighborhood.

towards the BS. Neighbors that belong to a $N_\pi(k)$ set are selected from $N_{<}(k)$ set, so $N_\pi(k)$ consists of some nodes $i \in N_{<}(k)$. That implies (fig.3):

$$N_\pi(k) \subset N_{<}(k); \quad (26)$$

VI. FINAL REMARKS

Large bunch of routing and communication algorithms for Wireless Sensor Networks is energy aware or cluster oriented with neighborhood changing very rarely. Our proposal is also based on nodes cooperation within a neighborhood but instead of using cluster heads for data transmission it takes advantage of a conceptual framework of directed cooperation. Such approach comprehends many sophisticated distributed algorithms in a universal and flexible way that is suitable for analyses.

Any decision and action that is undertaken within the WSN is actually performed by nodes based on their information about their vicinity (within a neighborhood). Relation based approach ensures coincidence of local node activity with globally defined requirements as directed cooperation is. In order to meet this global requirement, every single network node gathers all the information that allows aligning the transmission flow with the preferred direction. Hop distance and relations proposed in this paper ensure that the whole communication is directed towards the BS, there are multiple paths to route messages from a particular node to the BS, and some nodes can be excluded from routing if necessary.

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