TrustMIX: Trustworthy MIX for Energy Saving in Sensor Networks

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\texttt{MIX} has recently been proposed as a new sensor scheme with better energy management for data-gathering in Wireless Sensor Networks. However, it is not known how it performs when some of the sensors carry out sinkhole attacks. In this paper, we propose a variant of \texttt{MIX} with adjunct computational trust management to limit the impact of such sinkhole attacks. We evaluate how \texttt{MIX} resists sinkhole attacks with and without computational trust management. The main result of this paper is to find that \texttt{MIX} is very vulnerable to sinkhole attacks but that the adjunct trust management efficiently reduces the impact of such attacks while preserving the main feature of \texttt{MIX}: increased lifetime of the network.

1 Introduction

Wireless sensor networks have received a great deal of attention from the research community during the last decade. One of the main challenges of sensor network design is to save the limited available energy in order to ensure long term functioning. A number of schemes have been proposed to minimize energy consumption at all layers, including the routing layer we are here interested in, see section 2.3. In a typical application, the network nodes have to propagate environmental information gathered by their sensors to base station. Most of the time, sensors use short-range radio transmission to save energy since the required transmission power increases super-linearly with the distance between sender and receiver. As a consequence, messages are propagated in a hop-by-hop fashion from the source to the base station and message routing becomes necessary. Many routing schemes have been proposed, typically, messages can follow a gradient established during the initialization phase of the network (nodes $n$ hops away from the base station send messages to nodes $n - 1$ hops away and so forth). In previous work, we have proposed one such gradient-based routing algorithm called \texttt{MIX} \cite{1, 2}. In \texttt{MIX}, we assume that sensors nodes can vary their transmission power, and thus their transmission range. This feature is used to send, occasionally, messages directly to the base station even if the base station is still quite far away. Typically, this can be used to

\textsuperscript{*}Research supported by the \textit{Swiss National Science Foundation} (SNF), ref. PBGE2 - 112864.
\textsuperscript{†}Swiss SER Contract No. 05.0030
avoid the last few hops around the base station where high traffic, congestion and high energy depletion can occur. The fact of avoiding the last few hops by sending a message directly to the base station is referred as ejecting the message. It has been shown in [1, 2, 3, 4] that a few occasional but well employed message ejections can greatly increase the overall network lifetime.

The \textsc{MIX} algorithm works well when all sensors cooperate. However, in some real settings, the cooperation assumption may not be valid. For example, a few sensors may lie about their current energy level to avoid having to forward messages or worse they may not forward messages when asked to do so. In the latter case, these misbehaving sensors carry out an attack commonly called sinkhole attack [5]. In this paper, we evaluate the impact of sinkhole attacks on \textsc{MIX}. In addition, we propose and evaluate an adjunct trust management mechanism to mitigate that impact. The organisation of the paper is as follows. In section 2, we survey the related work. In Section 3, we detail \textsc{MIX} and the model for adjunct trust management. Section 4 describes our evaluation testbed and presents our results. We draw conclusions and propose future work directions in section 5 and 6.

2 Related Work

In this section, we first give an overview of what we mean by computational trust management (section 2.1). Then, we survey how it has been used in the field of sensor network application (section 2.2) and in section 2.3 we give an overview of the main energy saving schemes for sensor networks.

2.1 Computational Trust Management Overview

In the human world, trust exists between two interacting entities and is very useful when there is uncertainty in the result of the interaction. The requested entity uses the level of trust in the requesting entity as a means to cope with uncertainty and to engage in an action in spite of the risk of a harmful outcome. There are many definitions of the human notion of trust in a wide range of domains, with different approaches and methodologies: sociology, psychology, economics, pedagogy. Romano’s recent definition tries to encompass previous work in all of these domains: \textit{Trust is a subjective assessment of another’s influence in terms of the extent of one’s perceptions about the quality and significance of another’s impact over one’s outcomes in a given situation, such that one’s expectation of openness to, and inclination toward such influence provide a sense of control over the potential outcomes of the situation} [6].

A computed trust value in an entity may be seen as the digital representation of the trustworthiness or level of trust in the entity under consideration: a non-enforceable estimate of the entity’s future behaviour in a given context based on evidence [7]. A computational model of trust based on social research was first proposed by Marsh [8]. Trust in a given situation is called the trust context. Each trust context is assigned an importance value in the range \([0,1]\) and a utility value in the range \([-1,1]\). Any trust value is in the range \([-1,1]\). Risk is used as a threshold for trusting decision making. Evidence encompasses the outcome of observations, recommendations and reputation. The propagation of trust in peer-to-peer networks has been studied by Despotovic and Aberer [9] who introduce a more efficient algorithm to propagate trust and recommendations in terms of computational and communication overhead. Such overhead is especially important in sensor networks as any overhead implies more energy spending. A high level view of a trust engine is depicted in 2
Figure 1. The decision-making component can be called whenever a trusting decision has to be made. Most related work has focused on trust decision-making when a requested entity has to decide what action should be taken due to a request made by another entity, the requesting entity. It is the reason that a specific module called Entity Recognition (ER) [10] is represented to recognise any entities and to deal with the requests from virtual identities. The decision-making of the trust engine uses two sub-components: a trust module that can dynamically assess the trustworthiness of the requesting entity based on trust evidence of any type stored in the evidence store; a risk engine that can dynamically evaluate the risk involved in the interaction, again based on the available evidence from the evidence store. A common decision-making policy is to choose (or suggest to the user) the action that would maintain the appropriate cost/benefit. In our sensor network application domain, we have to balance message ejection and forwarding rates, based on how much energy has to be spent in each case to successfully reach the base station. In the background, the evidence manager component is in charge of gathering evidence (e.g., recommendations, comparisons between expected outcomes of the chosen actions and real outcomes). This evidence is used to update risk and trust evidence. Thus, trust and risk follow a managed life-cycle.

Although Jøsang’s “subjective logic” does not use the notion of risk, it can be considered as a trust engine that integrates the element of ignorance and uncertainty, which cannot be reflected by mere probabilities but is part of the human aspect of trust. In order to represent imperfect knowledge, an opinion is considered to be a triplet, whose elements are belief $b$, disbelief $d$ and uncertainty $u$, such that

$$b + d + u = 1 \quad \text{for} \quad (b, d, u) \in [0, 1]^3$$

The relation with trust evidence comes from the fact that an opinion about a binary event can be based on statistical evidence. Information on posterior probabilities of binary events is converted in the $b$, $d$ and $u$ elements to a value in the range $[0, 1]$. The trust value $w$ in the virtual identity $S$ of the virtual identity $T$ concerning the trust context $p$ is:

$$w^T_{p(S)} = \{b, d, u\}$$

The subjective logic provides more than ten operators to combine opinions. For example, the recommendation ($\otimes$) operator corresponds to using the recommending trustworthiness $RT$ to adjust a recommended opinion. Jøsang’s approach can be used in many applications since the trust context is open. In this paper, we base our sensor trust values on this kind of triple and statistical evidence count, c.f. section 3.3.
2.2 Trust and Security in Sensor Networks

Wireless sensor networks contain hundreds of entities used to collect data from the environment where they are deployed. To save their limited available energy, low power and thus short range radio transmission is preferred. As a consequence, each sensor relies on its peers to forward collected data to a central entity, a base station. Limited in energy, sensors are also motivated to have a non-cooperative behaviour when it comes to relaying packets from other sensors. They can save power by not forwarding messages received from their neighbours. However, selfishness is not the only misbehaviour that a sensor network has to cope with. An attacker can as well compromise sensors and prevent packets from reaching their destination. Several types of attacks have been identified. A sensor behaving like a sinkhole will drop any packet it receives [5]. In a wormhole attack [11], two colluding sensors create a tunnel between them. The first sensor is situated in the proximity of the base station and relays the messages received by the second one. The tunnel is a fast path and will encourage the sensors to use it for routing. In a Sybil attack [12], a sensor claims to have multiple identities. For a routing protocol that uses several paths to the destination, a Sybil attack can advertise one path as several ones. Additionally, it can be correlated with sinkhole or wormhole attacks.

A first line of defense is the distribution of private keys to each sensor. But sensors are low cost devices, without tamper proof hardware, thus a captured sensor will permit access to its cryptographic material. Key management schemes [13, 14] try to increase network resilience to sensor capture while maintaining the performance objectives and minimizing the resulting cost of lower network connectivity due to sensors which do not share similar secret keys. There is a trade-off between the energy spent, the amount of memory used for protection and the security level reached [15]. Static keying means that sensors have been allocated keys off-line before deployment. The easiest way to secure a network is to give a unique key at pre-deployment time but if only one sensor is compromised the whole network is compromised and it seems viable to extract the key from one sensor as they are cheap and not so well protected (in non-military application scenarios). The second approach is to have pair-wise keys for all sensors on each sensor, which is impractical due to the memory constraints on the sensors. Dynamic keying means that the keys can be (re)generated after deployment: it creates more communication overhead but stronger resilience to sensor capture. Radio transmission consumes most of the energy spent for security mechanisms, encryption only represents 3% of the total energy consumption [15]. Thus, minimizing security transmission is important with regard to energy saving.

In [16], the authors argue that previous approaches relying on keying management and cryptographic means are not suitable for sensors due to their resource constraints or the fact that it is easy to recover their cryptographic material because they are cheap and not fully tamper-proof. In this paper, we do not follow the cryptographic approach. Instead, we focus on another way of detecting and preventing misbehavior by using computational trust management as presented section 2.1. Several mechanisms have been already proposed for mobile ad-hoc networks and wireless sensor networks. They are concerned with making decisions on whether to cooperate or not with their peers based on their previous behaviour. The information used to build the reputation value of neighbours is collected mainly by direct interaction and observation. Although it is accurate, it requires some time before enough evidence has been collected. In our scenario, where sensors are static, there is more time to build trust among neighbour sensors since they do not move. If recommendations are used,
the reputation of the sensors that provide the recommendations has to be taken into account. In this latter case, it may also generate vulnerabilities to false report attacks.

Existing trust models have different approaches to such reputation building and decision making problems. CORE [17] builds the reputation of a sensor as a value that is increased on positive interactions and decreased otherwise. It also takes into account positive ratings from the neighbours. If the aggregated value of the reputation is positive, the sensor cooperates, otherwise it refuses cooperation. CONFIDANT [18] considers only negative ratings from the neighbours. In order to compute a reputation value, different weights are assigned to personal observation and reported reputation. RFSN [19] uses only positive ratings and models the reputation value as a probabilistic distribution, by means of a beta distribution model. A sensor will cooperate with the neighbours that have a reputation value higher than a threshold. In [5], computational trust based on direct observations to mitigate both sinkhole and wormhole attacks is used. However, this work only covers the Mobile Ad-hoc NETwork (MANET) Dynamic Source Routing (DSR) protocol [20]. They cover two trust contexts: TPP, Packet Precision for wormhole; and TPA, Packet Acknowledgment for sinkholes. They combine the two trust contexts. If a sensor is suspected to be a wormhole, the combined trust value \( T \) is 0. Otherwise TPP is equal to 1. TPA is a counter that is incremented each time a sensor is used to forward a packet and an acknowledgement has been received before a timeout; it is decreased otherwise. The inverse of the combined trust value simply replaces the default cost of 1 in the LINK CACHE of the standard DSR protocol. If it is a wormhole the cost is set to infinity.

In this paper, we are interested in evaluating how the \textit{MIX} data-gathering protocol for sensor networks, which is different from the protocols covered by previous work on sensor trust management, is impacted by sinkhole attacks with an emphasis on energy. In section 3.3 we present the computational trust management model we have chosen. One of the main requirement is to maintain the MIX energy saving property while guaranteeing efficient delivery of messages under sinkhole attacks using trust management.

2.3 Energy Saving Schemes for Sensor Networks

In Wireless Sensor Networks (WSN), one of the main constraints is to minimize energy consumption in order to maximize the lifespan of the network. Indeed, sensor nodes are usually battery powered [21, 22, 23]. In order to increase the lifetime of sensor networks, various energy saving schemes have been proposed. For example, multi-hop transmission techniques [24, 25], clustering techniques [26], alternating power saving modes [27], varying transmission levels with route selection [28], energy replenishment [29], multi-path routing [30], probabilistic forwarding techniques [31], mobile sinks [32, 33, 34], varying battery levels [35] or varying transmission ranges [36] are among possible approaches. For survey papers the reader may want to look at [37, 38, 39, 40]. Another possibility for network lifetime maximization is energy balancing, which is the approach we are interested in in this paper. In an energy balanced network, all the motes deplete their energy at the same rate. To our knowledge, energy balancing was first proposed in [41] to implement a sorting algorithm in WSN’s, [42] to solve a task allocation problem and in [43] to implement a data-gathering algorithm for WSN’s.

In this paper, we are interested in sensor networks accomplishing a data-gathering task, arguably the most common task for sensor networks. A data-gathering WSN is deployed over a region to be monitored and when a mote detects an event, it needs to report to the sink. To
do so, it is usual [38, 39, 40] to send messages to the sink in a hop-by-hop fashion, from node to node towards the sink. While this minimizes the total energy spent by the network, since the cost of sending a message from a mote to another grows like a power (greater or equal to 2) of the distance between motes [39, 40], this type of data-propagation leads to premature energy depletion of nodes close to the sink [43, 44, 45, 46, 47, 4, 2, 35, 36]. Indeed, nodes close to the sink are bottleneck nodes through which every message propagated through the network has to pass, when using a hop-by-hop routing algorithm. This heavy load of traffic on motes close to the sink brings them to deplete their energy rapidly. Unfortunately, when too many of those nodes run out of energy, the sink becomes disconnected from the network, thus putting the network down while there may be plenty of energy remaining in motes away from the sink. It thus seems that energy balancing is a particularly promising way of maximizing the lifespan of networks accomplishing a data-gathering task. We next present briefly the state of the art for this approach.

In [43], and then in [44], the same authors propose an energy balancing data-propagation algorithm based on a division of time in two different phases: during the first phase, sensors send data directly to the sink while, in a second phase, sensors send data in a hop-by-hop fashion. The duration ratio between the two phases is critical to ensure energy balance, and the adequate value is found through simulation. In [45] and then in [46], the authors propose to use a probabilistic algorithm to ensure energy balance. The network is divided into slices of sensors situated at the same hop distance to the sink in the Unit Disc Graph (UDG) associated to the WSN. The authors show that energy balance is achieved if a recurrence relation is satisfied between the probabilities, for each slice, that sensors eject messages directly to the sink. In [47] a more general case is considered, where the distribution of events is not known a priori but dynamically inferred by the base station by observation of the network. The optimal ejection probabilities for each slice are computed and broadcast in the network periodically. In [4], an algorithm is proposed to compute offline the parameters maximizing the lifespan of the network which is equivalent to the one from [45, 46] when an energy balanced solution exists. However, they extend the work from [45, 46] by also considering the case where the distribution of events and the topology of the network lead to a situation where an energy balanced solution does not exist, a case which had not been considered in previous work, and prove analytically that their algorithm produces an energy balanced and optimal solution when such a solution exists, and that in other cases the algorithm still outputs an optimal solution, although not energy balanced. Previous algorithms were useless when no energy balance solution exists. We would like to emphasize that all these approaches use a centralised algorithm to compute the optimal ratio of direct ejection to the sink and hop-by-hop sliding of messages. In [2], the MIX algorithm was proposed. Similarly to previous work, [2] considers that sensors may vary their transmission range. Short range is used to send messages to 1-hop away neighbours and occasional long-range transmission is used to send (or “eject”) messages directly to the sink, typically to avoid the last few bottle-neck hops around the sink forming a “hotspot” in the network. [2] also considers the possibility of using “medium range” transmissions. As an example, a message could be sent half-way to the sink. I.e., if the message is being sent by a sensor node located \( n \) hops away from the sink, a medium range transmission could send the message to a sensor node \( n/2 \) hops away from the sink. Medium range transmissions could be interesting, although they imply a number of technical challenges (e.g. how can a message be routed 5 hops away if the node only knows its 1 hop away neighbourhood?), however, [2] proves the surprising result that medium range transmissions are useless in the sense that they cannot increase the lifetime of
a network using a combination of short range transmission and long range ejections directly to the sink. We describe in detail the MIX algorithm in section 3.2.

3 Trustworthy MIX Model

The MIX algorithm, proposed in [2], is a distributed algorithm meant to maximize the lifespan of a wireless sensor network accomplishing a data-gathering task. In this scenario, sensor nodes are deployed over a region where some phenomenon is being monitored. When an event is detected by one of the motes, it data has the choice between sending a message directly to the sink (in this case we say the message is ejected to the sink) or sending it to one of its neighbour nodes (in which case we say the message is slid along the network). The mote which receives the message will be, in turn, faced with the same choice: eject or slide the message. The ejection feature of the MIX algorithm lowers the traffic load on nodes close to the sink, thus preventing the unwanted early energy depletion of sensors close to the sink described in section 2.3.

3.1 Sensor Network Model

Communication graph We take the common approach of considering a WSN composed of \( N \), a set of sensors represented by points in the Euclidean plane \( \mathbb{R}^2 \). One of them is a distinguished node \( S \) representing the sink. We use the unit disc graph (UDG), probably one of the most common communication graph models for sensor networks. The UDG is built by adding an edge between any pairs of sensors which are at distance at most 1 from one another. An edge represents a wireless link between two sensors (or the sink). It may be worth pointing out that the unit disc graph is an idealized communication graph model and that recently it has been emphasized that relying too much on the model can lead to erroneous results. In this work, we rely on the communication graph for simulation purposes only and there seem to be no reason to believe that the adjunct trust scheme we propose in this paper behaves differently in other real or modeled communication graph. We are thus confident that the UDG assumption is harmless in the context of this paper.

Energy consumption model As explained, sensors can either send data to a neighbour node in the UDG communication graph, or alternatively send data directly to the sink, which is the message ejection feature of MIX. We arbitrarily consider that a sensor \( n \) sending a message to one of its neighbours requires the sending sensor to spend 1 energy unit, whereas sending a message directly to the sink makes it spend \( \text{hop}(n)^2 \) energy units, where \( \text{hop} \) is the length of the shortest path from the sending node to the sink in the UDG (for simplicity we make the assumption that the UDG is connected). In other words, we consider that the attenuation factor for increasing transmission range is 2, and we make the pessimistic approximation that a sensor node \( n \) is at Euclidean distance \( \text{hop}(n) \) from the sink. As was explained in [45, 46], the arbitrary choice of 2 for the attenuation factor does not modify the global behavior of ejecting algorithms (although it changes numerical values in simulation).

Attacker model In order to simulate the sinkhole attacks, we consider that a subset \( A \) of the sensor motes \( N \) is composed of attacker motes. When receiving a message, those motes simply discard it, and in order to capture as many messages as possible, the attacker motes
lie about their remaining energy as well as their hop distance, pretending they have plenty of
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energy left (in the simulations, we set their energy level to infinity) and that they are closer
to the sink than any of their neighbours. Thus, the attacker motes apply a strategy which is
directly aimed at fooling the MIX algorithm since MIX considers motes to be good relays for
data propagation precisely when they have plenty of energy left, and when they are close to
the sink in terms of the hop distance, c.f. section 3.2 for a detailed description of MIX.

3.2 The Basic MIX Energy Saving Scheme

Cite [48, 49]

The MIX algorithm [1, 2] is a gradient based routing algorithm: when a node needs to send
a message it looks for its "lowest" neighbour and sends it the message. If a node is located
at a local minimum, it ejects the message directly to the sink, thus the ejection feature. In
MIX, the potential function is such that a node \( m \) is considered lower than a node \( n \) if

\[
\text{hop}(m) < \text{hop}(n)
\]
or if

\[
\text{hop}(m) = \text{hop}(n) \text{ and } \text{energy}(m) < \text{energy}(n)
\]

where \( \text{energy}(m) \) is the energy consumed by node \( m \) so far and \( \text{hop}(m) \) is the hop distance
from the mote to the sink. We give a more precise description of the MIX algorithm in the
pseudocode of figure 1.

**Algorithm 1** MIX Routing algorithm for sensor \( n \)

1: {When \( n \) gets a message, it will send it to \( \text{nextMote} \).}
2: \( n = \text{Sensor running the algorithm} \)
3: \( \text{nextMote} = \text{"not defined"} \)
4: for all node \( m \) among neighbours of \( n \) do
5: \( \text{if } \text{hop}(m) \geq \text{hop}(n) \text{ then} \)
6: \( \text{next} \)
7: \( \text{else if } \text{energy}(m) \geq \text{energy}(n) + \text{hop}^2(n) \text{ then} \)
8: \( \text{next} \)
9: \( \text{else if } \text{nextMote} \text{ is } \text{"not defined"} \text{ then} \)
10: \( \text{nextMote} = m \)
11: \( \text{else if } \text{energy}(m) < \text{energy}(	ext{nextMote}) \text{ then} \)
12: \( \text{nextMote} = m \)
13: \( \text{else if } \text{energy}(m) = \text{energy}(	ext{nextMote}) \text{ then} \)
14: \{Flip a coin to sort ties.\}
15: \( \text{nextMote} = m \text{ with probability 0.5} \)
16: end if
17: end for
18: \( \text{if } \text{nextMote} = \text{"not defined"} \text{ then} \)
19: \{If \( \text{nextMote} \) is not defined, we need to eject the message to the sink.\}
20: \( \text{nextMote} = \text{sink} \)
21: end if
22: return(\text{nextMote})
It may be noticed that in order to run on a mote, i.e. to make MIX fully distributed, it is required that each node has access to the remaining energy and hop distance of each of its neighbours. Each node is assumed to be aware of its own remaining energy (via its embedded electronics), and each node is assumed to know its own hop distance to the sink. This could typically follow from the initialisation phase of the network, during which a single flooding occurs from the sink. This implies that every node sends one message (assuming no collisions occur), although optimisation is possible, c.f. [50] for a proposition of our own. Knowing the hop distance of neighbours is easy, since it is a constant value in a static network. However, even in a static network, the energy values change. Therefore, keeping aware of the remaining energy of neighbour nodes, or at least an estimation of this value, will require some extra care.

As explained in [2], this could for example be implemented in a real WSN using standard piggy backing techniques, for example by including in the header of messages the remaining energy and ID of the sender.

3.3 Adjunct Trust Scheme

The trust scheme we propose is based on a trust function locally computed at the sensor level and using belief, disbelief and uncertainty values \((b, d, u) \in [0, 1]^3\) for each pair of nodes, as explained in section 2.1. We make the assumption that at each moment in time, for each node \(m\) and for each one of its neighbours \(n\), \(m\) knows the number \(s(m, n)\) of messages it has sent to \(n\), as well as \(r(m, n)\) and \(c(m, n)\) the number of messages \(m\) has sent to \(n\) which have been received by the sink and captured by one of the attacker motes respectively. In order to know the value of \(s(m, n)\), node \(n\) simply needs to count the messages it sends to \(m\). However, keeping track of \(r(m, n)\) and \(c(m, n)\) may be more difficult in a real WSN (in our simulations, those values are assumed to be available). Basically, what is required is some sort of transport layer protocol that permits to control when and if a message reaches destination. One way of implementing this in a real network would be to make the sink send acknowledgements (ACKs) when it receives a message. By broadcasting from time to time a list of (hash keys) of received messages, for example using a time division multiple access scheme (TDMA), the sink could let all sensors become aware of the safe reception of messages. This means however that sensors need to store hash tables of messages awaiting an ACK and need to listen for the ACKs from the sink, so there is an overhead in energy consumption and memory usage. We would like to stress that the long range broadcasting of ACKs by the sink is not a problem in scenarios where the sink has plenty of available energy, for example when the sink is plugged on the electrical network. Also, to prevent the attackers from sending tainted ACKs, a static keying cryptographic scheme could be used, c.f. section 2.2. Finally, in order to be aware of the number of captured messages \(c(m, n)\), the node \(m\) may simply set a time stamp for each message awaiting an ACK and need to listen for the ACKs from the sink, so there is an overhead in energy consumption and memory usage. We would like to stress that the long range broadcasting of ACKs by the sink is not a problem in scenarios where the sink has plenty of available energy, for example when the sink is plugged on the electrical network. Also, to prevent the attackers from sending tainted ACKs, a static keying cryptographic scheme could be used, c.f. section 2.2. Finally, in order to be aware of the number of captured messages \(c(m, n)\), the node \(m\) may simply set a time stamp for each message awaiting an ACK from the sink. If the time stamp is reached, the message is considered captured. With this approach, the belief \(b\), the disbelief \(d\) and the uncertainty \(u\) that node \(m\) holds towards \(n\), c.f. section 2.1, are defined as \(b = \frac{r(m,n)}{s(m,n)}\), \(d = \frac{c(m,n)}{s(m,n)}\) and \(u = 1 - \frac{r(m,n) + c(m,n)}{s(m,n)}\). Finally, we define the trust that node \(m\) has in \(n\) to be

\[
\text{trust}(m,n) = \frac{s(m,n) + r(m,n) - c(m,n) + 1}{s(m,n) + r(m,n) + c(m,n) + 1}
\]

\[
s(m,n) > 0 \quad \Rightarrow \quad \frac{2b + u}{2b + 2d + u} \quad s(m,n) \rightarrow \infty \quad \Rightarrow \quad \frac{2b + u}{2b + 2d + u}
\]
The “+1” term in the definition above is just used to avoid confidence dropping to 0 in the case where a single message has been sent and captured (i.e. when \( s = c = 1 \) and \( r = 0 \)), and it leads to a vanishing term when \( s(m, n) \) tends to infinity. The trustMIX algorithm we propose is a generalisation of the MIX algorithm using the above trust function. The idea in trustMIX is that when a node \( n \) considers neighbours to which it could forward messages, it will refuse to take into consideration those it distrusts. More precisely, when a sensor node loops over neighbours to which it would possibly forward a message (i.e. while in the for loop of algorithm 1), the sending node \( n \) simply disqualifies any neighbour \( m \) with probability \( 1 - trust(n, m) \). trustMIX is thus a randomized algorithm. Our explanations are made precise in Algorithm 2.

**Algorithm 2** Routing algorithm for sensor \( n 

```plaintext
n = Sensor running the algorithm
nextMote = "not defined"
for all node m among neighbours of n do
  x = random(0, 1)
  if x > trust(n, m) then
    next
  else
    {Carry on with the main loop of the MIX algorithm}
    if hop(m) ≥ hop(n) then
      next
    else if energy(m) ≥ energy(n) + hop^2(n) then
      next
    else if nextMote is "not defined" then
      nextMote = m
    else if energy(m) < energy(nextMote) then
      nextMote = m
    else if energy(m) = energy(nextMote) then
      nextMote = m with probability 0.5
  end if
end if
if nextMote = "not defined" then
  nextMote = sink
end if
return(nextMote)
```

Please notice that in the case where the network is trustworthy, the algorithm is identical to the original MIX algorithm since the trust between pairs of sensors is 1. As we shall see in the evaluation section 4, simulations show that trustMIX manages to side-step sinkholes and to deliver a significant fraction of messages to the sink, while preserving the main feature of MIX: increased lifespan of the network.
4 Evaluation

We analyse our algorithm through simulations. To conduct simulations, we consider a circle of radius $r$ and randomly and uniformly scatter $n$ sensor nodes in the circle. A sink $S$ is placed at the center of the circle. Optionally, $a$ attacker motes performing a sinkhole attack may be scattered (randomly and uniformly) in the network. We divide time in rounds and each round is divided in two phases: During the event detection phase, we randomly pick a non-attacker mote and make it detect an event by incrementing the size of his message stack by one. During the message propagation phase, each sensor with a non-empty message stack sends exactly one message. The sending mote runs algorithm 2 to decide to which neighbour the message is going to be slid, or if it should eject the message directly to the sink. For simulation purposes, we use the following parameters: $r$ is the radius of the circle in which nodes are initially deployed, $d$ is a density factor and $p$ is the fraction of attacker motes added. Given $r$, $d$ and $p$, we set $n$ to $n = \pi \cdot r^2 \cdot d$ and $a = p \cdot n$. In order to evaluate the performances of our proposed algorithm, we run in parallel and on the same network topology and same generated events three scenarios. In the first scenario (1), no attackers are placed in the network and the motes run the MIX algorithm 1. In the second scenario (2), the attacker motes are deployed and the MIX algorithm is used again, without adjunct trust management (i.e. the attack will be fully effective). Finally, the third scenario (3) uses the adjunct trust scheme described in section 3.3 and the motes run the trustMIX algorithm 2 as a counter-measure to the sinkhole attack.

4.1 Basic MIX attack results

We observe that the MIX protocol is vulnerable to sinkhole attacks (scenario 2). The three plots of figure 2 show the result of our simulations when $r$ and $d$ are set to 8 and 4 respectively, and when $p$ takes values in 10, 25 and 50. We observe that even with a relatively small number of attacker motes (left-hand side plot of figure 2), attacker motes advertising themselves as having plenty of energy and being close to the sink rapidly become attractive to the MIX routing protocol, and soon manage to hijack an large proportion ($80 - 90\%$) of the total traffic. Figure 2 shows the instantaneous arrival rates at the sink. In fact, the curve is smoothened by taking the average over 100 time steps. More precisely, since one message is generated in the network at each time step, the smoothened instantaneous percentage of

![Figure 2: Impact of sinkhole attacks on MIX](image)

smoothened by taking the average over 100 time steps. More precisely, since one message is generated in the network at each time step, the smoothened instantaneous percentage of
arrived messages at time $t$ is defined as $f(t)$, with $f(t) = \sum_{i=0}^{99} S_{rcv}(t - i)$, for each value of $p = 10$, $p = 25$ and $p = 50$, and where $S_{rcv}(t)$ counts messages received by the sink at time $t$.

4.2 MIX with Trust Management Attack Results

The trust engine we use builds confidence levels between pairs of nodes. Trustworthy motes are more likely to be selected for message forwarding, whereas attacker motes will be avoided. The aim of the trustMIX algorithm is to detect and avoid attacker nodes and to run the normal MIX algorithm from [2] on the remaining trustworthy motes. Success for trustMIX would mean that messages get delivered to the sink while preserving the main feature of the MIX algorithm: increased lifetime for the network. We shall show that this is indeed the case.

4.2.1 Evaluating the Attenuation of the Sinkhole Attack

We start by evaluating the ability of the trustMIX algorithm to route messages to the sink in a network under a sinkhole attack (scenario 3) and show that it succeeds in letting messages bypass the sinkholes. The left-hand side of figure 3 shows the instantaneous\(^1\) percentage of messages reaching the sink for fixed radius $r = 8$ and $d = 4$, and when the percentage of attackers increases ($p = 10$, $p = 25$ and $p = 50$). For $p = 10$, we see that trustMIX rapidly manages to safely deliver 80% of the traffic to the sink. The proportion of delivered traffic increases over time, as the trust engine adjusts trust values for pairs of nodes, and soon reaches about 90%. This should be compared to figure 2, where we see that MIX delivers only about 10% of the traffic safely, even for a small number of attackers ($p = 10$). The comparison of the three curves on the left-hand side plot of figure 3 shows that the more attacker nodes there are, the more messages get captured and the longer it takes for the trust engine to adjust accurate trust values for pairs of motes. However, even under harsh conditions ($p = 50$, c.f. lower curve of the left-hand side plot of figure 3), the trustMIX algorithm is rapidly capable of delivering 50 – 60% of the traffic safely (again, compare this to figure 2, where only about 10% of the traffic reaches the sink for the MIX algorithm even for $p = 10$). On the right-hand side of figure 3, we see that even for $p = 50$ the trustMIX algorithm manages to route safely about 80% of the traffic, but it needs more time to adjust correct trust values. Summarizing, we see that trustMIX successfully attenuates the effect of a sinkhole attack on the network by successfully delivering an important fraction of the total traffic.

4.2.2 Impact of the Sinkhole Attack on Energy Consumption

Next, we turn to evaluating the energy consumption of trustMIX (scenario 3) in comparison to the energy consumption of MIX in scenario 1.

Convention 1 In this section, it is implicit that trustMIX is run with scenario 3 and that MIX is run with scenario 1.

We would like to point out that when a message is captured by a sinkhole, the network stops consuming energy for routing it: this gives an unfair energy advantage to trustMIX, which may have less messages to route all the way to the sink than MIX. Therefore, unless stated otherwise, we adopt the following convention in this section:

\(^1\)Like in section 4.1, we the curves are smoothened by taking the average over 100 time steps.
Convection 2 When considering energy consumptions, it is implicit in this section that we always consider energy consumptions per delivered message to the sink and per time unit.

In figure 4, we compare the average and the maximum instantaneous\(^2\) energy consumptions of MIX and trustMIX for different values of \(p\). The average and maxima are taken over all sensor nodes of the network. As a preliminary remark, we observe that the maximum and

\(^2\)Again, taken as an average over 100 time steps
Looking at the maximum energy consumption of trustMIX, we see it is significantly greater than for MIX. This is even more so when there are many attackers (central and right-hand side plots of figure 4), and when the network has had little time to adjust trust values (i.e. when time is small). The first interpretation of this observation is that under a sinkhole attack, the energy balancing feature of MIX is not well preserved by trustMIX and some nodes spend more energy than others. This seems to be a weakness of trustMIX, however a careful analysis shows that the key objective of MIX, to increase the lifespan of the network, is preserved by trustMIX even under a sinkhole attack. In other words, we shall next explain why the maximum energy consumption is not a good metric to measure the lifetime of trustMIX under a sinkhole attack. On the contrary, in [4, 2], the maximum energy consumption is taken as a measure of the lifetime of the network. The authors argue that the maximum energy consumption is a good measure of lifetime for routing algorithms where most of the traffic is sent hop-by-hop, including MIX, but see [4] for details.

In figure 5, we look at the distribution of energy consumption in the network for trustMIX, plotting the position of sensors (more precisely the distance to the sink) against the total energy consumption (for each sensor) divided by the total elapsed time, i.e. this is the average power, for each sensor, in Joules per seconds (or Energy units per second, c.f. section 3.1). Please notice that in figure 5 we do not follow convention 2 of dividing the energy by the number of received messages.

![Energy consumption per sensor](image)

Figure 5: Detailed observation of energy consumption for trustMIX

As a first observation, we see that low energy consumption is preserved for motes close to the sink for all values of $p$. Furthermore, when there are just a few attackers ($p = 10$) almost all nodes are energy balanced (left-hand side plot of figure 5).

On the contrary, when the network is under a sinkhole attack performed simultaneously by many attackers ($p = 25$ and $p = 50$, center and right-hand side plots of figure 5), nodes away from the sink deplete their energy reasonably but noticeably faster than those close to the sink.

However, unlike the early energy depletion of nodes close to the sink that occurs for hop-by-hop routing strategies (c.f. section 2.3), the energy depletion of motes away from the sink does not imply disconnection of the sink from the network and thus does not put the whole network down. Instead, when the network is under attack by a high number of attacker motes, sensors away from the sink will deplete energy slightly faster, thus reducing the sensing range of the whole network but without actually diminishing the network lifespan, since as seen on
figure 4, the average energy consumption of trustMIX is similar to the one of MIX.

5 Conclusion

We have proposed trustMIX, a fully distributed and simple algorithm for wireless sensor networks which extends and secures the MIX algorithm from [2] when submitted to massive sinkhole attacks. Our three main results are to show (1) that the algorithm successfully lets most of the data avoid sinkholes (2) preserving the main features of MIX: increased lifespan of the network. We observe (3) that the mix TRUST algorithm trades off energy consumption from the motes situated on the outer boarder of the network for increased security. In other words, if the network becomes subject to a sinkhole attack, it successfully avoids the sinkholes for most messages, but slowly becomes blind at its peripheral, as nodes away from the sink deplete their energy faster. This phenomenon seems to have less impact when the attacker motes are not too numerous ($p = 10$ in our simulations). We also see that time is a crucial factor, since the trust mechanism needs time to detect the attacker motes, and the higher the percentage of attacker nodes, the more time the trust engine needs to secure the network.

6 Future Work

The trustMIX mechanism we propose shows that MIX can be efficiently secured in the scenarios we have considered. Future work will analyse parameters which have not been considered in this paper. Such parameters include the deployment of attackers in a non-uniform manner (for example, a region of the network could be attacked or attackers could be deployed in strategic regions, e.g. close to the sink). Also, we have only considered the ratio of delivered to captured messages in the case of uniform events generation, but it would be nice to investigate whether messages away from the sink are more likely to get captured than those close to the sink. This will eventually lead future work to propose enhanced versions of the trustMIX algorithm we propose in this paper. For example, if messages away from the sink are more likely to be captured, a multi-path strategy could be applied to guarantee a lower percentage of captured messages. The amount of message redundancy would be dynamically computed taking into account parameters such as the distance to the sink, the trust levels of neighbours and possibly the importance of the message: if a message is labelled very important, it may be worth spending more energy to ensure higher probability of delivery.

References

[1] Olivier Powell, Aubin Jarry, Pierre Leone, and Jose Rolim. Gradient based routing in wireless sensor networks: a mixed strategy. arXiv.org automated e-print archives, 2005. Report CS-0511083.

[2] Aubin Jarry, Pierre Leone, Olivier Powell, and Jose Rolim. An optimal data propagation algorithm for maximizing the lifespan of sensor networks. In IEEE International Conference of Distributed Computing in Sensor Systems (DCOSS), 2006.

[3] Olivier Powell, Pierre Leone, and Jose Rolim. Energy optimal data propagation in wireless sensor networks. arXiv.org automated e-print archives, 2005. Report CS-0508052. Journal version in Journal of Parallel and Distributed Computing.
[4] Olivier Powell, Pierre Leone, and Jose Rolim. Energy optimal data propagation in sensor networks. *Journal of Parallel and Distributed Computation*, 67:302–317, 2006.

[5] A A Pirzada and C S McDonald. Circumventing sinkholes and wormholes in ad-hoc wireless networks. 2005.

[6] D Romano. The Nature of Trust: Conceptual and Operational Clarification. PhD thesis, Louisiana State University, 2003.

[7] Trustcomp online community. http://www.trustcomp.com.

[8] S. Marsh. Formalising Trust as a Computational Concept. PhD thesis, Department of Mathematics and Computer Science, University of Stirling, 1994.

[9] Zoran Despotovic and Karl Aberer. Trust and reputation management in p2p networks, July 6-9, 2004.

[10] JM Seigneur. Trust, Security and Privacy in Global Computing. PhD thesis, Trinity College Dublin, 2005.

[11] Y. Hu, A. Perrig, and D. Johnson. Wormhole detection in wireless ad hoc networks, 2002.

[12] James Newsome, Elaine Shi, Dawn Song, and Adrian Perrig. The sybil attack in sensor networks: analysis & defenses. In *IPSN ’04: Proceedings of the third international symposium on Information processing in sensor networks*, pages 259–268, New York, NY, USA, 2004. ACM Press.

[13] Mohammed A. Moharrum and Mohamed Eltoweissy. A study of static versus dynamic keying schemes in sensor networks. In *PE-WASUN ’05: Proceedings of the 2nd ACM international workshop on Performance evaluation of wireless ad hoc, sensor, and ubiquitous networks*, pages 122–129, New York, NY, USA, 2005. ACM Press.

[14] H. Chan, A. Perrig, and D. Song. Random key predistribution schemes for sensor networks, 2003.

[15] David D. Hwang, Bo-Cheng Charles Lai, and Ingrid Verbauwhede. Energy-memory-security tradeoffs in distributed sensor networks. In *ADHOC-NOW 2004*, volume 3158 of *LNCS*, 2004.

[16] Saurabh Ganeriwal and Mani B. Srivastava. Reputation-based framework for high integrity sensor networks. In *SASN ’04: Proceedings of the 2nd ACM workshop on Security of ad hoc and sensor networks*, pages 66–77, New York, NY, USA, 2004. ACM Press.

[17] Pietro Michiardi and Refik Molva. Core: a collaborative reputation mechanism to enforce node cooperation in mobile ad hoc networks. In *Proceedings of the IFIP TC6/TC11 Sixth Joint Working Conference on Communications and Multimedia Security*, pages 107–121, Deventer, The Netherlands, 2002. Kluwer, B.V.

[18] Sonja Buchegger and Jean-Yves Le Boudec. Performance analysis of the confidant protocol. In *MobiHoc ’02: Proceedings of the 3rd ACM international symposium on Mobile ad hoc networking & computing*, pages 226–236, New York, NY, USA, 2002. ACM Press.
[19] Saurabh Ganeriwal and Mani B. Srivastava. Reputation-based framework for high integrity sensor networks. In SASN '04: Proceedings of the 2nd ACM workshop on Security of ad hoc and sensor networks, pages 66–77, New York, NY, USA, 2004. ACM Press.

[20] D. Johnson. Routing in ad hoc networks of mobile hosts. In Workshop on Mobile Computing Systems and Applications, Santa Cruz, CA, U.S., 1994.

[21] Jan M. Rabaey, M. Josie Ammer, Julio L. da Silva, Danny Patel, and Shad Roundy. Picoradio supports ad hoc ultra-low power wireless networking. Computer, 33(7):42–48, 2000.

[22] Brett Warneke, Matt Last, Brian Liebowitz, and Kristofer S.J. Pfister. Smart dust: Communicating with a cubic-millimeter. Computer, 34(1):44–51, 2001.

[23] Michael J. Sailor and Jamie R. Link. "smart dust": Nanostructures devices in a grain of sand. Chemical Communication, 11:1375–1383, 2005.

[24] C. Intanagowiwat, R. Govindan, and D. Estrin. Directed diffusion: A scalable and robust communication paradigm for sensor networks. In 6th International Conference on Mobile Computing (MOBICOM). ACM/IEEE, 2000.

[25] I. Chatzigiannakis, S. Nikoletseas, and P. Spirakis. Smart dust protocols for local detection and propagation. In 2nd Workshop on Principles of Mobile Computing (POMCO), pages 9–16. ACM, ACM Press, 2002.

[26] W.R. Heinzelman, A. Chandrakasan, and H. Balakrishnan. Energy efficient communication protocol for wireless microsensor networks. In 33th Hawaii International Conference on System Sciences (HICSS), 2000.

[27] C. Schurgers, V. Tsiatsis, S. Ganeriwal, and M. Srivastava. Topology management for sensor networks: Exploiting latency and density. In 8th International Conference on Mobile Computing (MOBICOM). ACM/IEEE, 2002.

[28] J. Chang and L. Tassiulas. Energy conserving routing in wireless ad hoc networks. IEEE INFOCOM, 1:22–31, 2000.

[29] L. Lin, N.B. Shroff, and R. Srikant. Asymptotically optimal power-aware routing for multihop wireless networks with renewable energy sources. Proceedings of INFOCOM’05, 2005.

[30] X. Hong, M. Gerla, H. Wang, and L. Clare. Load balanced, energy-aware communications for Mars sensor networks. Aerospace Conference Proceedings, 2002. IEEE, 3:3–1109, 2002.

[31] A. Boukerche, I. Chatzigiannakis, and S. Nikoletseas. Power-Efficient Data Propagation Protocols for Wireless Sensor Networks. SIMULATION, 81(6):399–411, 2005.

[32] J. Luo. Mobility in Wireless networks: friend or Foe - network design and Control in the Age of Mobile Computing. PhD thesis, School of Computer and Communications Science, EPFL, Switzerland, 2006.
[33] J. Luo and J.-P. Hubaux. Joint mobility and routing for lifetime elongation in wireless sensor networks. In 24th INFOCOM, 2005.

[34] J. Luo and J.-P. Hubaux. Mobility to improve the lifetime of wireless sensor networks: A theoretical framework. In Workshops of the Second International Conference on Distributed Computing in Sensor Systems (DCOSS), 2006.

[35] M.L. Sichitiu and R. Dutta. Benefits of Multiple Battery Levels for the Lifetime of Large Wireless Sensor Networks. In NETWORKING 2005: 4th International IFIP-TC6 Networking Conference, Lecture Notes in Computer Science, pages 1440–1444. Springer Berlin/Heidelberg, May 2005.

[36] S. Olariu and I. Stojmenovic. Design Guidelines for Maximizing Lifetime and Avoiding Energy Holes in Sensor Networks with Uniform Distribution and Uniform Reporting. In 25th Conference on Computer Communications (INFOCOM). IEEE Communications Society, IEEE Computer Society Press, April 2006.

[37] Azzedine Boukerche. Handbook of Algorithms for Wireless Networking and Mobile Computing. Chapman & Hall/CRC, 2005.

[38] A. Boukerche and S. Nikoletseas. Wireless Communications Systems and Networks, chapter Protocols for Data Propagation in Wireless Sensor Networks: A Survey, pages 23–51. Kluwer Academic Publishers, 2004.

[39] Jamal N. Al-Karaki and Ahmed E. Kamal. A taxonomy of routing techniques in wireless sensor networks. In Mohammad Ilyas and Imad Mahgoub, editors, Handbook of Sensor Networks: Compact Wireless and Wired Sensing Systems, pages 6.1–6.24. CRC Press, 2005.

[40] Kemal Akkaya and Mohamed Younis. A survey on routing protocols for wireless sensor networks. Ad Hoc Network Journal, 3/3:325–349, 2005.

[41] M. Singh and V. Prasanna. Energy-optimal and energy-balanced sorting in a single-hop wireless sensor network. In First International Conference on Pervasive Computing and Communications (PERCOM). IEEE, 2003.

[42] Y. Yu and V.K. Prasanna. Energy-balanced task allocation for collaborative processing in networked embedded system. In Conference on Language, Compilers, and Tools for Embedded Systems (LCTES), June 2003.

[43] W. Guo, Z. Liu, and Guangbin Wu. An energy-balanced transmission scheme for sensor networks. In Poster Session of the First International Conference on Embedded Networked Sensor Systems (SenSys). ACM, IEEE Computer Society Press, November 2003.

[44] Z. Liu, D. Xiu, and Weihua Guo. An energy-balanced model for data transmission in sensor networks. In 62nd Semiannual Vehicular Technology Conference, September 2005.

[45] C. Efthymiou, S. Nikoletseas, and J. Rolim. Energy balanced data propagation in wireless sensor networks. In Best papers of the 4th International Workshop on Algorithms for Wireless, Mobile, Ad Hoc and Sensor Networks, 2004.
[46] C. Efthymiou, S. Nikoletseas, and J. Rolim. Energy balanced data propagation in wireless sensor networks. *Wireless Networks (WINET) Journal*, 2006.

[47] P. Leone, S. Nikoletseas, and J. Rolim. An adaptive blind algorithm for energy balanced data propagation in wireless sensor networks. In *The First International Conference on Distributed Computing in Sensor Systems (DCOSS)*, number 3560 in Lecture Notes in Computer Science. Springer Verlag, June/July 2005.

[48] Olivier Powell and Sotiris Nikoletseas. Simple and efficient geographic routing around obstacles for wireless sensor networks. In *Workshop on Experimental Algorithms (WEA)*, pages 161–174. Springer-Verlag, 2007.

[49] Olivier Powell and Sotiris Nikoletseas. Geographic routing around obstacles in wireless sensor networks. Technical Report cs.DC/0703094, Computer Science ArXiv of Distributed, Parallel and Cluster Computing, Mars 2007.

[50] Pierre Leone, Luminita Moraru, Olivier Powell, and Jose Rolim. A localization algorithm for wireless ad-hoc sensor networks with traffic overhead minimization by emission inhibition. In *Proceedings of ALGOSENSOR’06*, 2006.