

# BitSurfing: Wireless Communications with Outsourced Symbol Generation

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**Abstract**—Nano-IoT enables a wide range of ground-breaking technologies, but face implementation challenges due to the extremity of the scale. Space restrictions pose severe power supply considerations, to the point where just a few packet transmissions are sufficient to deplete state-of-the-art supplies. In turn, this translates to difficulties in developing efficient protocols even for basic operations, such as addressing and routing. The present work proposes a new network adapter architecture that can address these challenges. The BitSurfing adapter does not generate packets and, hence, abolishes the need for the corresponding transmission circuitry and power consumption. Instead, it relies on an external symbol generator. The BitSurfing adapter reads incoming symbols, waiting for intended messages to appear in the symbol stream. A short (1-bit), low-energy pulse is then emitted to notify neighboring nodes. BitSurfing adapters are shown to exhibit perpetual (and even battery-less) operation, ability to operate without medium access control, while being completely transparent to applications. Moreover, their operation is event-driven, allowing for clock-less implementations. The new adapters are evaluated in a simulated multi-hop nano-IoT network and are shown to offer nearly-perfect packet delivery rates and practically no collisions, under any congestion level.

**Index Terms**—Nano-IoT, wireless, network adapter, low-complexity, energy-efficiency, security.

## I. INTRODUCTION

Nano-IoT will extend the reach of smart control to the level of molecules and cells, with unprecedented impact in medicine and material manufacturing. Combating diseases within the human body via autonomous nanomachines, self-healing and self-monitoring materials are a few of the most visionary applications. Materials with software-defined electromagnetic behavior constitute applications under development, paving the way for programmable wireless environments [1].

Nanonode architectures under research, especially the ones targeting the most visionary applications, seek to implement common components (receiver, transmitter, processor, memory, battery, sensor and actuator) down at the nanoscale. Among them, transceivers and batteries constitute the major roadblocks for manufacturing nanonodes [2]. Regarding the transceiver, studies have identified the  $THz$  band and graphene antennas as the most promising approaches [2]. Nonetheless, their energy consumption constitutes a major problem. Even exotic (hard to integrate) power supplies relying on energy harvesting can only scavenge energy for 1 packet transmission per approximately 10 sec [2]. This makes the development of even basic protocols—such as addressing and routing—highly challenging [3].

The present work contributes a novel network adapter for nano-IoT—the BitSurfer—that can overcome these shortcom-

ings. Its operating principle is unconventional, as it does not include creating and transmitting packets and, hence, no corresponding circuitry. Instead, the task of symbol creation is *outsourced* to an external entity, the symbol source. BitSurfing adapters simply listen to the symbol stream created by the source, and await for desired messages to appear within it. Simple 1-bit, low energy pulses are then used for notifying neighboring nodes to read their streams and extract the message intended for them. The present study details the benefits of BitSurfing adapters, which include transparency, perpetual, battery-less (by prospect) and Medium Access Control (MAC)-less operation. Moreover, the BitSurfing workflow is completely event-driven, meaning that they can be implemented as asynchronous chips [4]. Since power is not drawn on synchronized clock edges, the peak-power draw is much lower and better suited for battery-less systems. Furthermore this can favor miniaturization further, since common clock components—such as crystals and oscillators—are sizable, energy consuming (i.e., per tick) and one of the least-studied roadblocks towards manufacturing nano-IoT networks. BitSurfing is enabled by recent hardware advances, which have shown that wireless reception and data processing can be perpetually powered by the received carrier itself, without the need for a battery or any other power supply [5].

The paper is organized as follows. Section II provides the prerequisites. Section III details the BitSurfing architecture, while Section IV presents its design workflow. Evaluation takes place in Section V. Discussion and research directions are given in Section VI. The conclusion follows in Section VII.

## II. PRELIMINARIES

A core element of the BitSurfing model is the notion of *word cover time*, i.e., the expected time to find a specific string in an i.i.d. random binary sequence (*bit stream*). This problem has re-surfaced several times in the literature [6], leading to the following outcomes.

Let  $w$  denote a *word*, i.e., a specific binary sequence of '1's and '0's. Moreover, let  $\|w\|$  denote the size of the word  $w$  measured in number of bits. Then, the cover time  $CT(w)$  of word  $w$  is [6]:

$$CT(w) = 2^{\|w\|} + 2^{\|f(w)\|} + 2^{\|f(f(w))\|} + \dots \quad (1)$$

where  $f(w)$  is the failure function, defined as the longest prefix of  $w$  that is also its suffix. (By definition,  $f(w)$  returns an empty string if no such prefix exists). The summation in equation (1) continues as long as the exponent is greater than

zero. A C-language implementation of equation (1) can be found in the literature [7].

When we are not interested in a specific word, but rather for the cover time of any word of size  $\|w\|$  on average, the expression is simplified to  $CT(\|w\|) \sim \sqrt{\pi} \cdot 2^{\|w\|}$ , when  $\|w\| \rightarrow \infty$  [6]. For small  $\|w\|$  values (e.g.,  $\|w\| < 100$ ), which are of practical interest to this work, it holds that:

$$CT(\|w\|) \sim 2^{\|w\|} \quad (2)$$

Corresponding expressions exist for random streams modeled as Markov chains rather than i.i.d. processes [6]. The i.i.d. assumption is retained for ease of exposition.

### III. THE BITSURFING ADAPTER MODEL

The BitSurfing model proposes a new kind of network adapter that does not generate new physical data packets when transmitting information. Instead, it assigns meaning to symbols created by an external source as described below. It is noted that the operation of the novel adapter is transparent to the applications, which receive and request the delivery of data as usual, i.e., without being aware of the nature of the underlying adapter.

The proposed workflow is illustrated in Fig 1, involving two nodes equipped with BitSurfing network adapters and one symbol source. The source constantly produces new symbols and each BitSurfing adapter reads and stores them in a finite-sized, FIFO *stream buffer*. When the application logic of Node A requests the sending of data (i.e., a *word*) to Node B, the adapter waits until the word appears in its stream buffer. Then, it emits a single, short pulse (i.e., a single bit), which acts as a notification to Node B to scan its stream buffer for a valid word (i.e., contained within a predefined, common *codebook*). The first valid word found is passed on to the application logic of Node B.

We proceed to make note of some important aspects of the described workflow. Firstly, note that the stream buffers of two nodes may not be identical at a given time moment. Propagation delays and symbol processing time variations (for reading and storing symbols) may lead to relatively shifted buffer states. Secondly, the adapter workflow includes optional timeouts, to preclude that the adapter remains busy beyond a certain desired duration. The time for such events can be measured by counting symbol store events (in the buffer stream), rather than with a regular clock. Finally while a sender can enqueue simultaneous data send requests and treat them in a serial manner, a receiver can only respond to a received pulse if it is in an idle state. Pulses received by a busy receiving (Rx) interface are ignored.

Based on the described workflow, we make two important remarks:

- *The BitSurfing workflow is event-driven.*

This statement reflects the fact that the workflow does not require a hardware clock to time its operation. The adapter simply reacts to three simple events, i.e., the arrival of a new symbol, a `SendData()` request from the application, or the reception of a pulse. These attributes make the BitSurfing

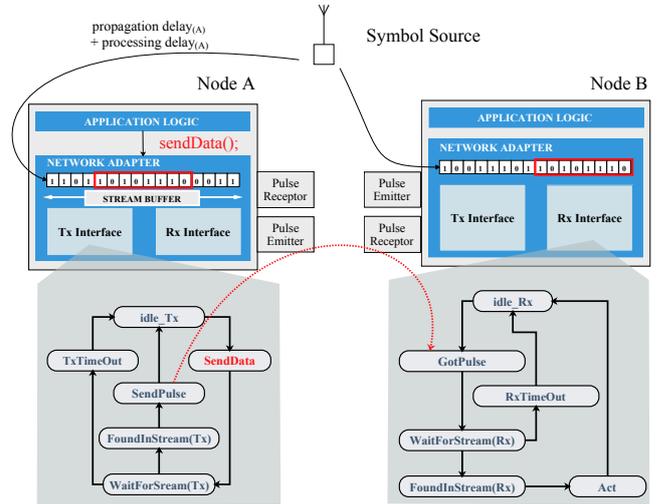


Fig. 1. Overview of the BitSurfing communication paradigm.

architecture eligible for implementation as an asynchronous chip. It is noted, however, that deriving specific hardware designs is an open challenge.

- *The symbol stream reception can vary across the network, without impacting the BitSurfing performance.*

In order for two nodes to communicate successfully, their symbol buffer contents may be relatively shifted, but should be otherwise identical. However, this condition needs only to hold *per network link*. This means that the symbol reception can vary across the network in general. *The only sufficient condition for BitSurfing is that neighboring adapters derive the same (albeit shifted) bit stream.*

### IV. DESIGNING THE BITSURFING CODEBOOKS

In this Section we study the characteristics of word sets (i.e., the codebooks) that can be used for BitSurfing-based communications. The driving design goals are perpetual operation and payload maximization.

#### A. Perpetual operation

Perpetual operation is a major concern for nano-IoT networks. The power budget of each nanonode should remain positive, meaning that energy harvesting rate must at least match the energy expenditure rate. A BitSurfing adapter expends energy to read and process the symbol stream incoming from the source, and to send the occasional pulse, as described in Section III. However, experimental studies have shown that wireless reception and data processing can be perpetually powered by the received carrier itself, without the need for a battery or any other power supply [5]. Thus, we will assume that the BitSurfing adapter power consumption stems only from the occasional pulse emissions. It is noted that the pulses themselves could be potentially powered by the carrier as well. Nonetheless, in absence of experimental data, we will assume the more common case of the pulse emission system proposed by Jornet et al [2], which employs graphene nanoantennas for pulse creation and zinc-oxide nanowires for energy harvesting.

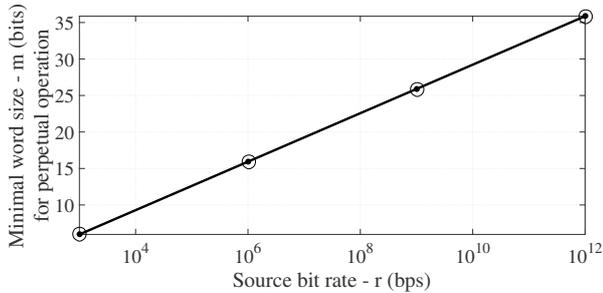


Fig. 2. The minimal word size for perpetual operation under varying source bit rates. The *Kbps*, *Mbps*, *Gbps* and *Tbps* cases are highlighted.

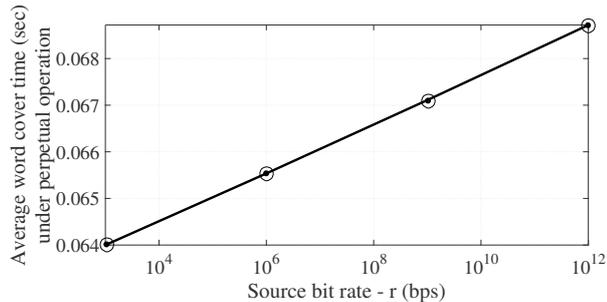


Fig. 3. The average word covering time under perpetual operation. The minimal word sizes of Fig. 2 are considered for each source bit rate case.

Let  $h$  denote the energy harvesting rate of a node, and let  $\epsilon$  be the energy expended for transmitting a single pulse per word of size  $\|w\|$ . The cover time is given by equation (2), measured in bits, or  $2^{\|w\|}/r$  measured in *sec*, where  $r$  is the bitrate of the symbol source (in *bps*). Perpetual operation requires that  $h$  is greater than the power drain, i.e.:

$$h \geq \frac{\epsilon}{2^{\|w\|}} \Rightarrow \|w\| \geq \|w\|_{min}, \|w\|_{min} = \left\lceil \log_2 \frac{\epsilon \cdot r}{h} \right\rceil \quad (3)$$

■ For a source bitrate  $r$  there exists a minimal word size  $\|w\|$  that yields perpetual operation.

Figure 2 shows the minimal word sizes for perpetual operation, for a range of bit source rates, assuming some common values for  $\epsilon = 1 pJ$  and  $h = 16 pJ/sec$  [2]. Indicatively, the  $r = 1 Kbps$ ,  $1 Mbps$ ,  $1 Gbps$  and  $1 Tbps$  cases correspond to 6, 16, 26 and 36-bit words.

It is interesting to note that the cover time (measured in *sec*) corresponding to the minimal word sizes of relation (3) is approximately constant. This outcome follows from equation (2), when  $\|w\| = \|w\|_{min}$ :

$$CT(\|w\|_{min}) = \frac{2^{\lceil \log_2 \frac{\epsilon \cdot r}{h} \rceil}}{r} \sim \frac{\epsilon}{h} \quad (4)$$

For instance, as shown in Fig. 3, the expected word cover time is approximately 66 *msec* for the studied source rates of 1 *Kbps* – 1 *Tbps*, while  $\epsilon/h$  yields  $1/16 sec = 62.5 msec$ .

Notice that the 62.5 *msec* cover time value may constitute a worst-case scenario for BitSurfing. These values are derived for ambient energy harvesting ( $\epsilon = 1 pJ$  and  $h =$

#### Algorithm 1 Process for calculating the codebook size.

**Inputs:** A specific prefix,  $p$  (e.g., '1101'); a word size  $\|m\|$ .

**Output:** The codebook size,  $max\_size$ .

- 1: **var**  $max\_size \leftarrow 2^{\|m\| - \|p\|}$ ;
- 2: **for all** binary words  $n$  so as  $\{\|n\| = \|m\| - \|p\|\}$
- 3:   **if**  $wrdfind(wrdcat(p, n), p) > 0$
- 4:      $max\_size \leftarrow max\_size - 1$ ;
- 5:   **end if**
- 6: **end for**

$wrdcat(a, b)$  : concatenates words  $a, b$ .

$wrdfind(a, b)$  : returns the index ( $\geq 0$ ) of the last occurrence of word  $b$  in word  $a$ , or  $-1$  if not found.

16 *pJ/sec* [2]) and not for the carrier-feed operation intended in this work [5]. While the  $h$  value corresponding to the latter cannot be derived without an actual implementation at nano-scale, it is expected that it will be much higher than ambient energy harvesting. Carrier feed is a type of wireless power transfer, which is not only more structured, but can also be freely set to a conveniently high level. Higher  $h$  values can reduce the outcome of eq. (4) even to  $\mu sec$  levels.

#### B. Payload maximization

As described in Section III, searching the stream buffer for valid words is the core operating principle of the BitSurfing adapter. For reasons of hardware simplicity and search efficiency, the codebook (i.e., the set of valid words) should support the self-synchronizing property [8]. This means that a search within a binary string  $S$  comprising any concatenation of codebook words  $S : \{w_1 + w_2 + \dots\}$ , yields only the words  $w_1, w_2, \dots$ , and in the exact concatenation order. An approach for achieving this property is described by the following remark:

■ A codebook comprising words that: i) begin with a prefix  $p$ , and ii)  $p$  is not found anywhere else within each word, is self-synchronizing.

The prefix approach has additional advantages:

- The buffer search can only look for  $p$  and then be triggered to check if the remaining  $\|w\| - \|p\|$  bits form a valid word.
- The search can occur at a fixed index position, since the buffer contents move towards the FIFO direction. (Eventually, the word will reach the fixed index position).
- Invalid words are easily discarded: once the  $p$  bits are found, they should not be encountered again for the remaining  $\|w\| - \|p\|$  bits. If they are indeed encountered again, the adapter can safely discard and ignore the previous occurrence of  $p$  (forward detection of valid words).

However, a disadvantage of the prefix approach is that it naturally limits the number of valid words (and, hence, the payload per word), making them less than the total  $2^{\|w\|}$  possible combinations. The process denoted as Algorithm 1 provides a straightforward way for calculating the size of a valid codebook, for a given prefix and a word size. Figure 4 illustrates the largest codebook sizes for several word and prefix sizes. It is shown that for every word size there exists

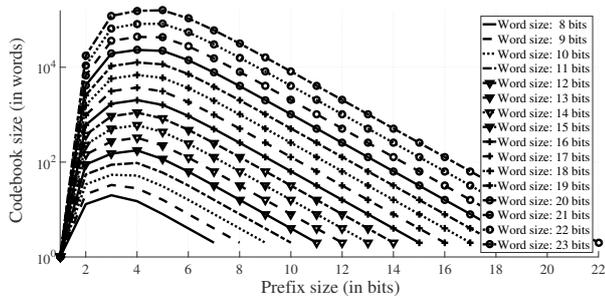


Fig. 4. The codebook size (in number of valid words) for varying word prefix bits. Several total word sizes are presented.

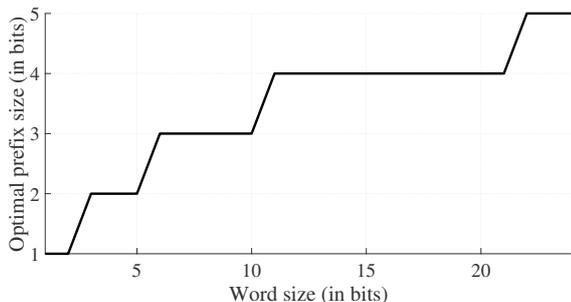


Fig. 5. Vertical cut of Fig. 4 showing the optimal prefix size (i.e., yielding the largest codebook) per word size.

a prefix size that offers the largest codebook. This is also illustrated in Fig. 5—a vertical cut of Fig. 4—which summarizes the optimal prefix sizes for given word sizes. For instance, words with  $11 \leq \|w\| \leq 21$  yield an optimal prefix of size 4.

Not all prefixes of equal size yield the same codebook size. Figure 6 shows the outputs of Algorithm 1 for 16-bit words and all possible 4-bit prefixes. The last six prefixes ('0001' to '1110') yield the largest codebook size of  $\sim 2100$  words.

One final consideration for choosing the best prefix (and the corresponding codebook from Algorithm 1) is the cover time distribution of the words it contains. As shown by equation (1), each word generally yields a different cover time. Thus, in Fig. 7: i) we obtain the codebooks for each of the '0001' to '1110' prefixes of Fig. 6 using Algorithm 1, and ii) calculate the expected cover time of each word therein. The box-plots express the cover time distribution for each codebook/prefix. The '0111' and '1000' prefixes exhibit the smallest cover time variance (albeit a marginal one), and can both be chosen to produce codebooks for the studied, 16-bit word case.

Having described the process of designing the BitSurfing adapters and codebooks, we proceed to evaluate a complete nano-IoT network setup with BitSurfing adapter-equipped nodes.

### C. Security

Security is considered as one of the main concerns in nano-IoT [9]. Authorization and authentication is paramount for mission-critical applications such as in medicine (e.g., in-body nano-IoT) and in mission-critical industry (structural control

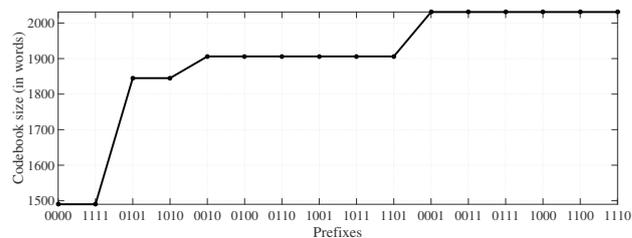


Fig. 6. Case study of 4-bit prefixes for 16-bit words. The six rightmost prefixes yield the largest codebooks.

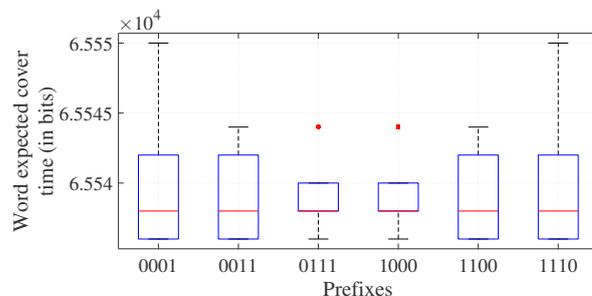


Fig. 7. Word cover time distribution for the codebooks pertaining to the six best prefixes of Fig. 6. The '0111' and '1000' prefix cases offer the (marginally) smallest cover time deviation.

of materials). However, extreme hardware restrictions do not allow for a classic, cryptography-based approach. In that sense, new approaches to security are required.

Symbol generation outsourcing provides a degree of novelty that can facilitate security. The node codebooks can be customized per application instance, naturally containing the impact of potential hacking. Moreover, hard-wired implementation at nano-scale means that the codebooks are naturally protected against direct tampering (e.g., capturing and reverse-engineering a nano-IoT node). Finally, the dependence on an external power source naturally solves the problem of emergency shutting down a nano-IoT network. This can be directly accomplished by removing or powering off the source, rather than relying on some protocol mechanism that could fail for a multitude of common causes.

## V. EVALUATION

The following setup is simulated at bit-level in JAVA, using the AnyLogic discrete event modeling platform [10]. The platform is based on Eclipse, and provides state-of-the-art facilities for code visualization, general purpose optimization and automatic statistical evaluation of models. A free version of the platform is available for personal use [10]. The runs took place on commodity hardware (Intel i7 4770, 16GB DDR3). The simulation files are freely available upon request.

The evaluation considers a multi-hop nano-IoT network with identical, BitSurfing adapter-equipped nodes. The studied communication scenario is applicable to HyperSurfaces, a novel class of planar materials that can interact with impinging electromagnetic waves in a software-defined manner [1]. They

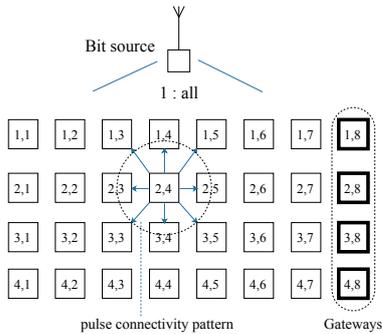


Fig. 8. The simulation setup, comprising one source and 32 nodes.

constitute a merge of nano-IoT and metamaterials [11]. Metamaterials comprise a two-dimensional pattern of a conductive material, the *meta-atom*, repeated periodically over a dielectric substrate. The form of the meta-atoms defines the electromagnetic response of the surface, exemplary including the reflection of the impinging wave at a custom angle (even at negative ones), full absorption, etc. The *HyperSurface* concept takes the metasurface concept one step further: it allows the formation of custom meta-atoms over it. A nano-IoT network embedded within the HyperSurface acts as the meta-atom sense and control factor. It senses and sends useful attributes of impinging waves to an external entity and receives back commands to “draw” meta-atoms by altering the local conductivity of the HyperSurface accordingly. For ease of exposition the evaluation focuses on the sensing direction, noting that the actuation direction is similar. With ease-of-manufacturing in mind, the source rate is set to  $r = 1 \text{ Mbps}$ .

**Setup.** We assume the system model of Fig. 1. Notice that, in accordance with Fig. 2, the chosen rate  $r = 1 \text{ Mbps}$  corresponds to 16-bit words in order to achieve perpetual operation. Moreover, based on Fig. 6 and 7, we adopt the ‘1000’ prefix which corresponds to a codebook of size 2100, i.e., 11 bits for payload per word (since  $\log_2(2100) \approx 11$ ). We will use these bits as follows: identifier of a sender node (5-bits), identifier of a recipient node (5-bits), and measurement data (1-bit) exemplary expressing whether the sensed current within a meta-atom surpasses a threshold. 5-bit identifiers can uniquely express  $2^5 = 32$  nodes, which explains the topology size of Fig. 1. (We note again that this limitation is due to the runtime consideration only). The node identifiers are considered hard-coded and well-arranged, as shown in the Figure. The four nodes placed at the right-most locations act as gateways to the external world. The pulse connectivity range shown is intended to increase the hops required for reaching a gateway, making successful delivery more challenging. As a general note, smaller pulse range also translates to less energy per pulse emission.

Finally, the steam buffer size is set to 30 bits, i.e., enough to accommodate 16-bits words and up to 14-bit buffer shifts due to variable propagation and processing delay. Each node has a random such delay, picked uniformly. Timeouts are set

TABLE I  
PACKET DELIVERY RATE VERSUS NETWORK CONGESTION LEVEL  
(NETWORK PACKETS CREATED SIMULTANEOUSLY).

Congestion	Packet delivery rate
1	100%
10	100%
20	99.62%
40	99.51%
60	99.51%
80	99.37%
100	99.36%

to  $10^6$  bits (i.e., 1 sec).

**Application logic.** When requested by the simulation, a node crafts a data packet (i.e., a word), comprising his identifier, the identifier of an immediate recipient node to its right picked at random, and a random measurement data. For instance, in Fig. 8, node (2, 4) picks any of the (1, 5), (2, 5), (3, 5) nodes at random as the immediate recipient. The packet is forwarded to the BitSurfing adapter, which starts waiting for it to appear in the stream buffer. If the adapter is busy, the packet is enqueued until the adapter becomes idle. When receiving a packet (by getting a pulse and retrieving the word from the stream buffer), a node first checks if itself is the immediate recipient. If not, the packet is ignored. If yes, it rewrites the immediate recipient list with one of its own right-hand neighbors. Gateways act as packet consumers only and do not create new ones.

**Run configuration.** We are interested in evaluating the BitSurfing-based communication in terms of successful packet delivery ratio (i.e., reaching the gateways) under various congestion levels, while logging transmission times owed to stream cover times and packet queuing delays. To this end, a single run comprises 100 successive packet creation phases. At the start of each phase, a number of packets are created simultaneously by randomly selected nodes. Naturally, more packets created simultaneously result into a more congested network. Once all packets have been delivered (or lost), a new creation phase begins. The following results refer to all 100 phases, to ensure high confidence in the logged values.

**Results.** Table I presents the delivery rates over all packet in each run, for different congestion levels. It is shown that BitSurfing offers an almost perfect delivery rate. The very few packet losses are owed to pulse collisions, i.e., when two pulses corresponding to different packets reach the same immediate recipient node at nearly the same time. Such collisions are highly unlikely to occur, given that pulses have *psec* duration [2], while the Rx stream processing time is also trivial ( $\mu\text{sec}$ ), as shown later in Fig. 11. This means that *BitSurfing adapters can operate without a medium access control mechanism, simplifying their hardware implementation.*

We proceed to study the transmission times in Fig. 9. The Figure illustrates the average time a word needs to cross a hop between two nodes, owed to (Tx) stream cover time and queuing time. Notably, *the cover time is invariant to network congestion*, as expected by equations (1) and (2).

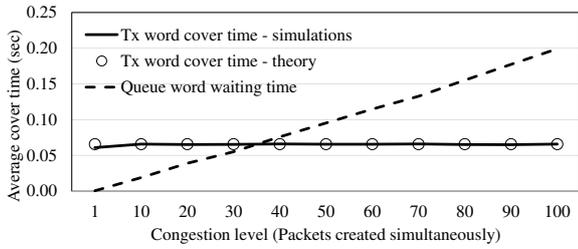


Fig. 9. Average time to traverse a network hop due to Tx word cover time and word queuing delay, under varying network congestion levels.

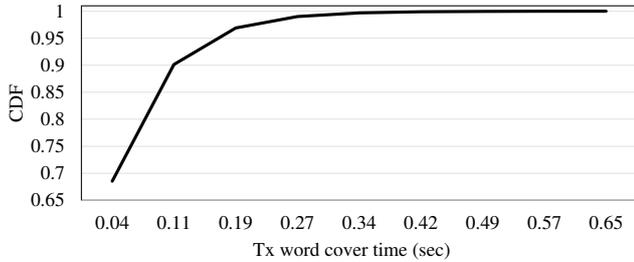


Fig. 10. CDF of the Tx word cover times (Congestion level: 100).

Moreover, the simulation are in agreement with the theoretical expectation (i.e.  $66\text{ msec}$ ) expressed by these equations. Thus, from a network congestion level and on, the queuing time becomes the dominant factor in the propagation delay.

Figure 10 proceeds to detail the CDF of the Tx cover times. It can be seen that there is a 80% probability that the cover time will be less than the average value of  $66\text{ msec}$ . Moreover, the cover time is almost certainly less than five times the average, i.e.,  $330\text{ msec}$ . Finally, it is worth noting that the Rx cover times are very low, as shown in the CDF of Fig. 11. When a receiving node gets an incoming pulse, the intended word is either already within the stream buffer or about to enter it. Thus, the Rx interface remains busy for very small time intervals ( $\mu\text{sec}$ ) before returning to the idle state. Thus, the collision probability becomes trivial, even for wireless networking standards, as shown in Table I.

## VI. DISCUSSION AND RESEARCH DIRECTIONS

BitSurfing communications were shown to exhibit some interesting benefits, summarized as follows:

- Simplified transmitter hardware: No packet transmission circuitry and potential for clock-less implementation.
- Simplified power supply: The BitSurfing adapters are intended to be fully carrier-fed and, thus, be completely battery-less and perpetually powered. This prospect is strongly supported by related implementations [5].
- Collision-less communication: In BitSurfing, a data packet exchange corresponds to one ultra-short pulse emission, regardless of the data packet size. Thus, collisions are practically inexistent, even at fully congested multi-hop networks.

However, BitSurfing requires a different hardware/software development style. Instead of approaching the hardware, the

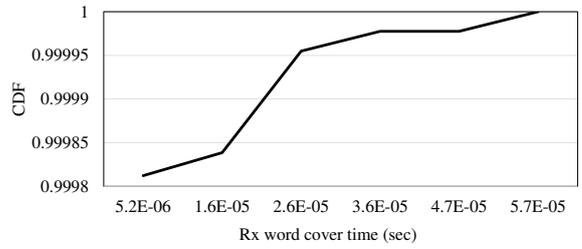


Fig. 11. CDF of the Rx word cover times (Congestion level: 100)

protocols and the application logic in a disjoint manner—i.e., the current common practice—BitSurfing dictates a close co-design process. The maximum number of nodes, the data latency requirements, the intended data format, all affect each other and define strict conditions that should be upheld by the BitSurfing hardware and protocols. Nonetheless, the enforced co-design comes with a clear workflow that was described in Section IV. This workflow readily provides the available BitSurfing parameterization corresponding to any requirements. There, it can actually guide and simplify the implementation process.

The co-design workflow and the hardware simplification benefits of BitSurfing constitutes it a promising approach for nano-IoT. Nanonodes are extremely restricted in terms of dimensions, which naturally calls for careful software/hardware co-design for optimal usage of the available space. The potential for operation without battery, transmission circuitry and MAC protocol facilitates miniaturization further. A consideration, however, is that the application scenario must allow for the presence of the external source that generates symbols and feeds the nanonodes with energy.

Finally, regarding the relation to existing studies, the BitSurfing model is novel, to the best of the authors' knowledge. A different concept that exhibits some conceptual similarity to BitSurfing is the *communication through silence* (CtS) [12]. CtS is ad-hoc, without external sources. To transmit a packet, a node emits a pulse to its neighbor. The recipient then starts counting from 0 in unary steps. The sender emits another, carefully synchronized pulse that notifies the recipient to stop counting and interpret the reached number as data. Collisions are very often: if another sender emits a pulse while the recipient is counting (a time-consuming task), it is still interpreted as a stop-counting signal. Moreover, perfect clocks are needed: if a pulse slips even by a single timeslot (e.g.,  $\pm 1$  clock tick), the perceived data will be erroneous. Thus, CtS does not exhibit the aforementioned benefits of BitSurfing in the context of nano-IoT.

### A. Research Directions

BitSurfing opens several interesting research directions, listed per adapter component:

**Symbol source.** The present study assumed an i.i.d. generated binary stream. Future extensions can study the cover time

in existing and widely-used symbol sources, such as WiFi, Cellular and DVB/T [13].

Moreover, extensions can study symbol sources specially designed for BitSurfing, rather than opportunistic ones. For instance, such a source can be restricted to generate and broadcast only valid words, rather than random bits. The schedule of such broadcasts and its adaptivity to the traffic pattern of the nanonodes is another open direction. Studies on broadcast scheduling can constitute the starting basis for this direction [14].

**Adapter codebook.** The preceding analysis and simulations considered codebooks with equi-sized words. Novel codebooks with variable size words can be developed, that match the traffic characteristics of the nano-IoT network [15]. For instance, smaller words (with smaller cover time) can be used to represent acknowledgment messages. This direction can be generalized as protocol/codebook co-design.

Additionally, codebooks can be designed to offer robustness against stream symbol reception errors. For instance, the lexicographical distance between words can be maximized [16], to limit the probability that an erroneously received word will be treated as another valid one. Model checking techniques can study the effects of such events [17], subsequently proposing protocol revisions as needed.

**Adapter hardware.** As discussed in Section IV-A, related studies provide strong evidence that the stream processing part of the BitSurfing adapters can be perpetually powered, without batteries [5]. Hardware-oriented studies are required to prove that the 1-bit pulse emissions can also be perpetually powered. This is expected to depend on the pulse emission hardware, the pulse propagation model (e.g., [18]), and the required pulse range. Note that multihop networks, like the one studied in Section V, require very short-range pulses.

Depending on the available power budget, hardware implementation can study “colored” pulses and multiple Rx and Tx interfaces per BitSurfing adapter. New `sendData()` requests from the application layer can then be forwarded to the Tx interface with the fewest enqueued requests, cutting down the word transmission times.

**Porting well-known protocols.** A promising point of the BitSurfing paradigm is that it may remove constraints in porting well-known protocols of wireless sensor networks to the nano-scale [19]. The perpetual and the MAC-less operation may allow for exchanging any number of packets, enabling the adaptation of common addressing and routing protocols (such as AODV) for nano-IoT. In the case of codebooks comprising small words (e.g., the 16-bit case simulated in Section V), data sessioning can undertake the task of transparently breaking down long messages as required [20].

## VII. CONCLUSION

The present work proposed a novel nano-IoT network adapter named BitSurfer. The novel adapter decouples the symbol generation from the communication process. BitSurfing nanonodes rely on an external generator which creates a continuous stream of symbols. The nanonodes read the

generated symbols awaiting the appearance of their intended messages, and then using 1-bit, low-energy pulses to notify each other. The operation of BitSurfing adapters is completely transparent to applications. Moreover, BitSurfing offers significantly simplified nanonode transceiver hardware, perpetual—and potentially completely battery-less—operation. Furthermore, the novel adapters can operate without medium access control, due to the very low probability of pulse collisions. The multi-hop network with BitSurfing-enabled nanonodes was simulated, exhibiting nearly perfect packet delivery rates and low delivery times.

## ACKNOWLEDGMENT

This work was funded by the European Union via the Horizon 2020: Future Emerging Topics call (FETOPEN), grant EU736876, project VISORSURF (<http://www.visorsurf.eu>).

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