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New Paradigms in Wireless Communication Systems

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Abstract. This paper discusses what a new paradigm can be in wireless communication systems of the twenty-first century. First, it suggests two directions for the new paradigm; one is “micro- and nano-device communication system” which is the projected scenario considering that the entities in source and destination have been shrinking throughout the history of wireless communication systems. The second direction is “networked robot system”, which emerges as a natural extension of mobile ad hoc networking where the networking is closely related to motion control of robots. Secondly, it shows two interesting research topics, “the new communication protocol design” and “signal processing”, respectively, that arise in the wake of the fusion between the two directions in the novel communication paradigm. Finally, it considers a new science of wireless communications in the twenty-first century.

Keywords: wireless communications, robotics, communication protocol, in-network signal processing

1. Introduction

Wireless communication system is only a means to realize the ultimate goal of communication with “whenever, wherever and whomever”. Since the beginning of 80’s, we have been so far making every effort on research and development of digital technologies to support communication systems with “higher data rates and higher reliability”, and as a result, we are now winning the end of “the twentieth century-type wireless communication systems”. Researches on wireless technologies for much higher data rates and much higher reliability are still being done, but they are based on combinations of CDMA (Code Division Multiple Access), OFDM (Orthogonal Frequency Division Multiplexing) and MIMO (Multiple Input/Multiple Output), all of which were born in the twentieth century, namely, they are located along a linearly extrapolated line of the twentieth century–type wireless communication technologies.

More than five years have passed in the twenty–first century and now we are really desiring a paradigm shift from the twentieth century–type to a twenty–first century–type in wireless communication systems. In this paper, we will consider what can be a new paradigm in wireless communication systems of the twenty–first century.

2. Shrinkage of Entities in Source and Destination

In the history of communication systems, the entities in source and destination are shrinking not rapidly but steadily. Telecommunication technology was first developed to support man–to–man communication. Looking at the physical scale of the entities in source and destination, they had the dimension of “meters”, so electro-magnetic waves with dimension of “millimeters” to “meters” were suited for them to use as a carrier to transmit information from source to destination. We have been so far successful in the development of man communication system, computer communication system and device (sensor) communication system, but the scales of the entities in those systems have not drastically changed, so such electro–magnetic waves have been able to be a carrier to convey information.

Figure 1 shows the change of physical scale of the entities in source and destination in the history of communication systems. Let us imagine a next wireless communication system, along with the scenario where they will continue shrinking. In the near future, micro– and nano–devices will be realized, so let us consider a communication system between such devices. As shown in Figure 2, electro–magnetic waves, which we have been so far successfully utilizing, cannot be a carrier in the system, because transmitter and receiver require antennas with the same size of the wavelength of the carrier to effectively transmit and receive a carrier. Therefore, micro– and nano–device communication system will require discussions on new technologies, such as what can be a carrier between the source and destination and what can be an energy source to support communications.

Furthermore, micro– and nano–devices will be no longer composed of and driven by electronic elements. For example, molecular computers are driven by soft–materials such as enzyme and protein. Therefore, molecular communication technology will be required where transmitter encodes nano–scale molecules as a carrier and receiver decodes the information by accepting them with bio–chemical reaction. Finally, Figure 3 summarizes the technologies required in micro– and nano–device communication systems.

3. A Natural Extension of Mobile Ad Hoc Networking

Cellular communication network provides randomly cruising mobiles with parts of an infrastructure network by means of base stations, and ad hoc communication network also provides randomly cruising mobiles with an infrastructure–less network. In other words, they try to

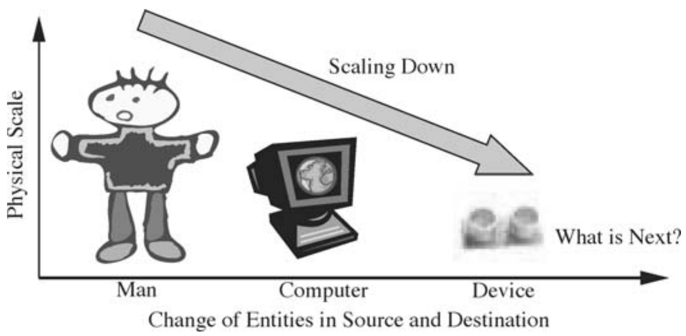


Figure 1. Change of physical scale in communications.

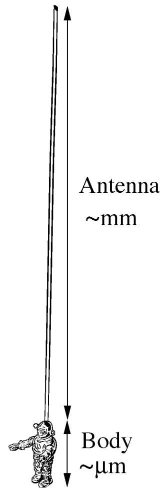


Figure 2. Which is a main part, antenna or body?

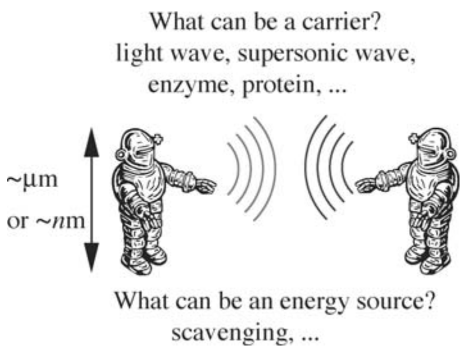


Figure 3. Micro– and nano–device communication system.

support communications among mobiles assuming that the motions of mobiles are perfectly random. On the other hand, in robotics, error never occurs in control channels between a centralized intelligence and remote devices such as hands and legs. In other words, it tries to transmit information to remote devices to control their motions assuming that channels are perfectly errorless. We think that these two research fields have been matured by the end of the twentieth century.

As mentioned in the above, we recognize that there is an assumption of a perfectness in communications or robotics, that is, communications assume a perfect randomness in the motions of mobiles whereas robotics assumes a perfectness in communication channels. Now, as a natural extension of mobile ad hoc networking, let us consider a situation where we remove both the perfectness in communications and robotics, that is, where we control the motions of mobiles to support communications among all mobiles. Here, the purpose of networking is to control the motions of all robots correctly whereas the purpose of motion control is to maintain reliable communications among all robots in erroneous channels. This means "to consider networking and motion control at the same level as well as at the same time."

This is called "robot networking" or "networked robots", and in the paper, we call it "networked robot system" because we want to deal with a group of all robots as a robot. Figure 4 shows an image of networked robot system.

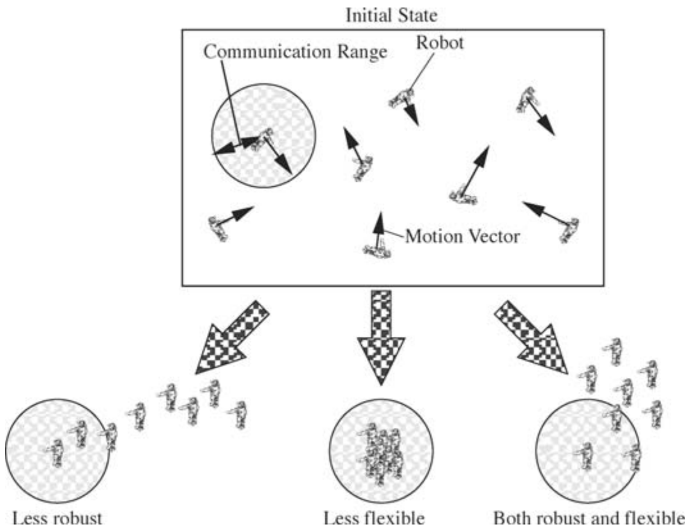


Figure 4. Networked robot system.

There are many interesting and challenging technological research topics in the networked robot system. For instance, assume that we will network *N* robots. If we have peer–to–peer connections to all robots, we need to have ${}_NC_2$ communication links. When *N* is large, say, more than 100, to have such a large number of links is not realizable. We need to introduce a layered structure in the network to geographically re–use the same communication links, so it is very challenging to design the structure of a network; how many layers are required in a network and how many links are required in a layer.

On the other hand, all robots have different coordinates in an initial state, so how to teach them a common coordinate and how to make them recognize their positions each other, of course, without GPS (Global Positioning System), are very interesting. Each robot should have more links to other robots to make the communication network be robust against the change of their positions, whereas the area where all robots can cover should be larger to give the system as a whole a function such as sensing. Therefore, it is very challenging to develop a distributed intelligence to keep the network of the system robust and the shape of the system flexible.

4. Overcoming the Current Design Paradigm for the Communication Protocols

The current communication protocols are built according to the layered paradigm and their ultimate objective is to deliver the data to the end user. Here the term *user* should be understood in a most general manner i.e. an entity that communicates with the application layer of the protocol stack. However, the current protocols are almost always oblivious with respect to the utility of the transferred information for the end user. Therefore, the communication network does a best–effort to transfer the data to the destination, irrespective of the semantics contained in that data.

Such an approach to the protocol design should be abandoned when the data communication is a part of a higher–layer task e.g. in a robot swarm,[1] which is a large system of networked robots. On one hand, it is true that a small group of macro-robots (say, at most order of magnitude smaller than a human) can be networked by using the existing wireless protocols. Nevertheless, if we consider a swarm of networked nano–robots, then the size (number of nodes) of the multi–agent system can be enormous, while the processing/communication/energy storage capabilities of each node (nano–robot) can be extremely modest. We can say that in such a large–scale system, the value of the individual data sent by a node can be judged by how the data affects the overall behavior of the system. Hence, it is not an imperative that a particular chunk of data reaches the destination reliably as long as the high–level task for the system as a whole is "on track". And the high–level task of the system should be a manifestation of a system–wide self–organization feature. Let us illustrate this point by an example.

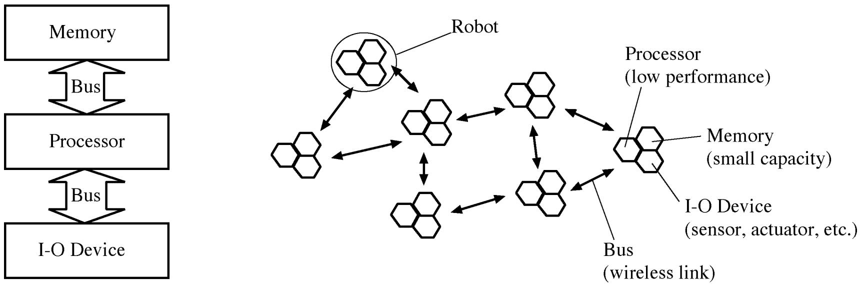
Example: A Swarm of Nano–Robots. Let us use the illustration from Figure 4. The absence of hard–wired connections among the nodes in the system makes provisions for flexible shaping and movement of the swarm. The price paid is the shared communication aether among the nodes. For the sake of robustness, we assume that there is no centralized control of the nodes' access to the communication medium. Let us assume that a certain number of nodes are trying to initiate movement of the swarm. Then these nodes start to broadcast their messages. The "acknowledgement" for these broadcasts is the movement of the swarm. Note that, in the absence of reliable data delivery, some nodes may remain static and thus be dropped from the swarm. The communication protocols should be designed with the following goals:

- If a *significant* number of nodes need to initiate coherent movement, then the movement message should be spread through the swarm. However, accidental randomized initiations of movement by a few nodes should be considered as noise and be suppressed.
- As long as the swarm has a *sufficient* size to perform the task, it is not important that the communication data has not reached some nodes and those nodes are dropped from the swarm.

Note the "soft" requirements that we have used to specify the swarm operation, which are quite different from the rigid performance requirements from the current communication protocols. The challenging question is: How the design framework for the "swarm" communication protocols should be different from the layered paradigm of the "normal" communication protocols?

5. In–Network Signal Processing

Considerations from a view point of signal processing reveal other aspects of the networked robot system. Figure 5(a) shows a typical architecture of existing computer systems. A high performance micro–processing unit, a memory with large capacity and input–output (I–O) devices are connected via wired bus of broadband and high reliability. By using the bus, the processor reads programs or data in the memory, writes data to the memory and also delivers the data to the I–O devices. On the other hands, Figure 5(b) is our interpretation of the networked robot system by using the computer terminology. The sensor to observe the environments can be regarded as one of the I–O devices. Each robot will be equipped with a processor and a memory, however, the requirements of very long lifetime, and hence extremely low power consumption, and low–cost implementation force them to be low–performance and small capacity. The wireless links among the robots are thought to be the bus to exchange the



(a) Typical Conventional Computer (b) Networked Robot System

Figure 5. Interpretation of networked robot system by using computer terminology.

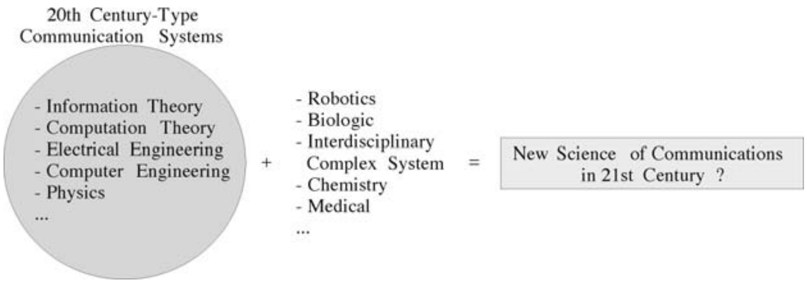


Figure 6. Integration of different sciences towards the new science of communications in the twenty–first century.

data. Furthermore, all the robots may not have the equivalent configurations. For example, only some of the robots could have processing functionality while the others have more simplified structure only with memory and sensing units. With such a consideration of the signal processing in the networked robot system, in other words, in–network signal processing is neither more nor less than designing a whole new computer architecture including the structure and the scheduling.

One may regard the networked robot system as nothing but a scaled–down version of existing distributed processing systems, such as grid computing, with the replacement of the wired links by the wireless links. However, there is a fundamental difference between the networked robot system and the existing distributed systems. Roughly speaking, the existing distributed processing systems aim at achieving higher performance in terms of processing speed, which has been also the goal of the conventional computers all along. In this sense, the distributed processing systems are the extensions of the conventional computers. On the contrary, the networked robot system can involve the data from unprecedented number of points of the spatial domain in the signal processing, since the large number of robots collect the raw data to be processed by themselves. Moreover, in the opposite direction, we can reach out to the environments from unprecedented numbers of points simultaneously, because each robot may be equipped with output devices. These outstanding features cannot be possessed by the extended systems of the conventional computers or signal processing methods.

The most challenging problem in the in–network signal processing lies in the restriction on the communications among the robots, therefore, “the design of the whole new computer architecture” will be the topic which researchers on wireless technologies must tackle. Efficient data combining approach, such as data fusion, will also play an important role in the design.

6. New Science of Communications?

The twentieth century–type research on wireless communication systems has been mainly based on information/computation theory, electrical/computer engineering, and physics. The combination of these different sciences has enabled us to tackle on many challenging problems encountered for developing diverse wireless technologies. However, the paradigm shift from the twentieth to twenty–first century–type wireless system is bringing more challenging problems as shown in the last four sections, which accordingly requires involvement of more different fields of science. Thus, the investigation of a networked robot system requires the integration of research on communication system and robotics. Many hints for efficient and robust task achievements with the swarm of nano–robots can be found in biology. That is, we could exploit the self–organizing and self–controlling features of bacteria, amoebae, insects, birds, etc. by which their actions are autonomously controlled to achieve certain task in spite of environmental changes and disturbances. The analysis of overall behavior emerging from local interactions in large–scale networked robots can be made with the new interdisciplinary science of complex system. Furthermore, the molecular communication technology exploiting bio–chemical reactions through enzyme and protein requires perspective of chemistry. Finally, the application of the nano–robot communications could unavoidably lead to novel paradigms in medicine and thus require symbiosis with the medical research area.

As shown in Figure 6, the integration of these different and diverse sciences will pave the way to the emergence of new science of communications in the twenty–first century. In fact, some integrations have already started e.g. in the field of swarm robotics, biologically inspired computing, etc.

7. Conclusions

Research on communication systems is dreamless in the sense that even if we hit on a great technology, it is rarely realized in practical systems. This is because being a standard is everything in communication systems. Through doing research on communication systems, we have unconsciously forgotten to have a dream. On the other hand, we do remember that we had many dreams in our childhoods. Don't give us a practical question of "What are the aims of the micro– and nano–device communication system and networked robot system?" We don't know the answer now but we surely know that there is a dream there.

Technologies can make a science fiction change to a science non–fiction. We do know it through the history of communication systems. In the movie of "Fantastic Voyage" by Isaac Asimov (1966), a submarine was shrunken to microscopic size and injected into a diplomat's blood stream with a small crew to save him. We believe the technologies developed in the micro– and nano–device communication system and networked robot system will make the story be a science non–fiction.

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References

1. J.S. Brown and R.R. Burton, "Diagnostic Models for Procedural Bugs in Basic Mathematical Skills", *Cognitive Science*, Vol. 2, No. 2, pp. 155–192, 1978.

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